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Composite Based EHV AC Overhead Transmission Lines

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Publication date:
2010

Document Version
Publisher's PDF, also known as Version of record

Technical University of Denmark

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PhD Thesis, January 2010

DTU Electrical Engineering
Department of Electrical Engineering

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Release date: January 2010
Category: 1 (public)

Edition: First

Comments: This report is part of the requirements to achieve the PhD in Electrical Engineering at the Technical University of Denmark.

Preface

The present PhD Thesis is submitted as a part of achieving the PhD degree at the department of Electrical Engineering at the Technical University of Denmark. The PhD project have been carried out in the period from January 2006 to December 2009. The PhD project has been fully financed by the Danish Transmission System Operator Energinet.dk.

I would to thank my supervisors Dr. Joachim Holbøll and Dr. Søren D. Mikkelsen for their involvement in the PhD project. A thanks also goes to Aksel G. Sørensen, who served as supervisor the first two years of the project, and to Gunnar Kyed, both for their continued interest in the project. Furthermore I would also like to express my appreciation to all my colleagues at Energinet.dk and at CET/EES/ELC, DTU Electrical Engineering who have helped and contributed with good spirit throughout the project.

During the project several participants from the industry have also contributed to the project. A great thanks goes to the participants in the international monitoring group. A special thanks goes to Svenska Kraftnät and STRI, especially Dr. Jan Lundquist, for allowing me to do my research stay in one of the world's largest high voltage hot spots.

Finally, many thanks to my family for their support throughout the PhD project and for their continued faith in me and a loving thanks to my girlfriend for being the person she is and for her support.

Kgs. Lyngby, January 2010

Thomas K. Sørensen

Summary

Overhead lines at transmission level are the backbone of any national power grid today. New overhead line projects however are at the same time subject to ever greater public resistance due to the lines environmental impact. As full undergrounding of transmission lines at extra high voltage (EHV) levels are still not seen as possibility, the future expansion of transmission grids are dependent on new solutions with lessened environment impact, especially with regard to the visual impact.

In the present Thesis, composite materials and composite based overhead line components are presented and analysed with regard to the possibilities, limitations and risks widespread application of composite materials on EHV AC overhead transmission lines may present.

To form the basis for evaluation of the useability of composite materials, different overhead line projects aimed at reducing the environmental impact are analysed with regard to their visual impact reducing design steps. These are used to form the basis for overhead line system design ideas, which are analysed with regard to application of composite materials and components.

Composite materials and components, when applied in EHV systems, are exposed to electrical, mechanical, thermal and environmental ageing mechanisms. Experiences and tests examining the effect of the ageing mechanisms are reviewed and discussed in the Thesis.

Standards and guidelines for dimensioning of overhead line systems are presented and composite based high voltage components are examined with respect to current loadability and required dimensions due to voltages and mechanical loads.

The Thesis is concluded with a discussion on composite materials' influence on electrical line parameters when introduced into EHV overhead lines. Furthermore general conclusions on the possibilities, limitations and risks of application of composite materials and composite components are outlined.

The main conclusions of the Thesis are; that composite materials based components are today available for the EHV range on a commercial basis with some limitations on towers and post insulators, that the use of composite materials alone only introduces small impacts with regard to improving the environmental impact of overhead lines; and that composite based components offer several advantages compared to components conventionally applied in overhead line systems.

Dansk Resumé (Danish Summary)

Luftledninger på transmissionsniveau er rygraden i et hvert nationalt el-transmissionsnet nu til dag. Samtidig er nye luftledningsprojekter dog emne for stadig stigende offentlig modstand på grund af luftledningernes miljøbelastning. Da fuld kabellægning af transmissionslinjer på EHV (extra high voltage) niveau stadig ikke anses for at være muligt, er fremtidig udbygning af transmissionsnet afhængige af nye løsninger med mindskede miljøbelastninger, specielt med henblik på de visuelle belastninger.

I den forhåndenværende afhandling præsenteres kompositmaterialer og kompositbaserede luftledningskomponenter med hensyn til de muligheder, begrænsninger og risici udbredt anvendelse af komposit materialer i EHV AC luftningssystemer måtte udgøre.

Til at danne basis for evaluering af anvendeligheden af kompositmaterialer, analyseres forskellige luftledningsprojekter rettet mod at reducere deres miljøbelastning med hensyn til de træk, der reducerer den visuelle belastning. Trækkene anvendes til at danne basis for luftledningsdesign, som analyseres med hensyn til anvendelse af kompositmaterialer og kompositbaserede luftledningskomponenter.

Kompositmaterialer og kompositbaserede komponenter er udsat for elektriske, mekaniske, termiske og miljømæssige ældningsmekanismer, når de anvendes i EHV luftledningssystemer. Erfaringer og test, der undersøger effekterne af ældningsmekanismerne, granskes og diskuteres i afhandlingen.

Standarder og vejledninger for dimensionering af luftledningssystemer præsenteres og kompositbaserede højspændingsprodukter undersøges med hensyn til deres strøm-belastbarhed og dimensioner, der er nødvendige på grund af systemspændingen og mekaniske laster.

Afhandlingen afrundes med en diskussion af kompositmaterialers indvirkning på elektriske linjeparametre ved introduktionen i EHV luftledningslinjer. Yderligere anføres generelle konklusioner vedrørende de muligheder, begrænsninger og risici anvendelse af kompositmaterialer og kompositbaserede komponenter udgør.

Hovedkonklusionerne i afhandlingen er; at kompositbaserede luftledningskomponenter i dag er kommercielt tilgængelige for alle spændingsniveauer i EHV gruppen dog med nogle begrænsninger for master og støtteisolatorer, at anvendelse af kompositmaterialer alene kun medfører små ændringer med hensyn til at forbedre de miljømæssige belastninger af luftledningssystemer, og at kompositbaserede luftledningskomponenter tilbyder adskillige fordele sammenlignet med komponenter, der traditionelt har været anvendt i luftledningssystemer.

Contents

Nomenclature

α	Material constant, page 131	-
γ	Density, page 131	kg/m^3
γ_F	Partial factor for mechanical loads, page 134	-
γ_M	Material partial factor, page 134	-
γ_C	Partial factor for construction and maintenance loads, page 135	-
γ_G	Partial factor self-weight, page 135	-
γ_I	Partial factor for ice loads, page 135	-
γ_K	Partial factor for exceptional loads, page 135	-
γ_P	Partial factor for conductor tensile loads, page 135	-
γ_W	Partial factor wind loads, page 135	-
λ	Line wavelength, page 157	m
μ_0	Magnetic field constant, page 158	H/m
ρ_{dc}	Resistivity, page 131	Ωm
σ	Mechanical stress, page 116	N/mm^2
τ	Time constant, page 129	s
θ	Temperature, page 126	°C
ε	Elongation, page 114	-
ε_0	Dielectric constant, page 158	-

ε_H	Elastic elongation, page 114	-
ε_θ	Thermal elongation, page 114	-
ε_{Creep}	Plastic or creep elongation, page 114	-
A	Conductor cross section, page 115	mm^2
A_K	Exceptional (security) loads, page 135	N
C	Heat capacitance, page 126	J/kg · °C
C	Line capacitance, page 158	F
c	Specific heat capacity, page 131	J/kgK
c_x	Position in relation to neutral axis, page 137	m
$CS(x)$	Conductor swing, page 121	m
D	Conductor sag, page 111	m
d	Conductor diameter, page 120	mm
d_i	Inner diameter of cylinder, page 138	m
D_M	Mean geometric phase-to-phase distance, page 158	m
d_o	Outer diameter of cylinder, page 138	m
D_{50Hz}	Basic power frequency clearance, page 100	m
D_{el}	Basic electrical clearance, page 100	m
D_{pp}	Basic electrical clearance between phases, page 100	m
E	Elasticity modulus, page 115	Pa
E_d	Design value of actions/forces, page 134	N
$f\,(U)$	Probability of overvoltage, page 104	-
$F\,(U_W)$	Probability of withstand voltage below U_W, page 104	-
F_d	Design load, page 134	N
F_K	Predicted load, page 134	N
G_K	Self-weight of components, page 135	N
H	Horizontal line tension, page 110	N

h_M	Mean conductor height above ground, page 158	m
I	Current, page 126	A
I_K	Ice load, page 120	N/m
I_M	Area moment of inertia, page 137	m^4
k	Conductor weight factor, page 121	-
K_a	Altitude correction factor, page 107	-
K_g	Gap correction factor, page 107	-
K_z	Correction factor for 50 % U_W deviation, page 107	-
K_{cs}	Statistical correction factor, page 108	-
L	Conductor length in span, page 111	m
L	Line inductance, page 158	H
l	Line length, page 157	m
$L(x)$	Conductor length in relation to vertex, page 111	m
L_B	Beam length, page 137	m
l_k	Insulator connection length, page 121	m
m	Mass, page 126	kg/m
n_2	Number of subconductors, page 158	-
P	Force on single point, page 137	N
P_{cr}	Critical load for buckling of beam, page 138	N
P_{max}	Theoretical steady-state stability limit for power, page 157	W
Q_C	Convective cooling, page 126	W/m
Q_R	Heat radiation, page 126	W/m
Q_S	Solar heating, page 126	W/m
Q_{CK}	Construction and maintenance loads, page 135	N
Q_{IK}	Ice loads, page 135	N
Q_{PK}	Conductor tensile loads, page 135	N

Q_{WK}	Wind loads, page 135	N
R	Resistance, page 126	Ω
R	Statistical risk of flashover, page 104	-
r	Radius, page 138	m
r_B	Equivalent conductor bundle radius, page 158	m
R_d	Structural design resistance, page 134	N
R_K	Characteristic resistance, page 134	N
S	Span width/length, page 111	m
SIL	Surge impedance loading, page 157	W
t	Time, page 117	s
U	Voltage or overvoltage, page 104	V
u	Deflection, page 137	m
U_m	Highest voltage for equipment, page 104	V
U_S	Highest system voltage, page 105	V
U_W	Withstand voltage, page 104	V
$U_{2\%}$	Withstand voltage resulting in 2 % flashovers, page 108	V
$U_{90\%}$	90 % withstand voltage, page 108	V
U_{rp}	Representative overvoltage, page 104	V
U_W	Withstand strengh, page 104	V
$V_{R,pu}$	Receiving end voltage, page 157	pu
$V_{S,pu}$	Sending end voltage, page 157	pu
w	Specific conductor weight, page 110	N/m
w_F	Distributed load, page 137	N/m
x	Distance from vertex of catenary curve, page 110	m
X_C	Capacitive reactance, page 158	Ω
X_L	Inductive reactance, page 158	Ω

$y(x)$	Height above vertex of catenary curve, page 110	m
y_0	Conductor sag at 0 °C, page 121	m
Z_C	Line surge impedance, page 158	Ω
SCD	Specific creepage distance, page 105	mm/kV
USCD	Unified specific creepage distance, page 105	mm/kV

Abbreviations:

CFO	Critical flashover voltage
CG	Conductor galloping
CS	Conductor swing
EDS	Every day stress
EHV	Extra high voltage
EPDM	Ethylene propylene diene monomer
MDT	Maximum design temperature
NNA	National normative sspect
PD	Partial Discharge
RBS	Rated breaking strength
RTS	Rated tensile strength
SCD	Specified creepage distance
SPS	Site pollution severity
TSO	Transmission System Operator
USCD	Unified specific creepage distance

Chapter 1

Introduction

Overhead line systems have been essential for the distribution of power from the point of production to the consumers since the introduction of electrical power. Ever higher voltage levels have been used to transport more power at lower losses. Today voltage levels have been standardised and are only slowly increased to new levels and many overhead lines have since been replaced by cables at lower voltage levels in many countries around the world. However at extra high voltage levels (300 kV – 700 kV) and above overhead transmission lines is still the only acceptable option for transportation of power over long distances without excessive losses and adequate security of supply on a wide scale at present.

Overhead transmission line are today mostly based on the same materials as they were fifty to sixty years when great parts of the European transmission grids where build. Components (insulators, conductors and towers) based on composite materials have slowly been introduced over the last decades yet these are still not widely spread. At the same time, the resistance to overhead line systems have over the last decades increased in the general public, especially with regard to the construction of new overhead lines due to their environmental (especially electromagnetic fields and aesthetic) impact.

The introduction of composite materials in overhead line transmission systems have shown that composite materials are advantageous when it comes to strength versus weight, expansion with temperature, needed physical dimensions and corrosion resistance compared to conventional materials such as wood, glass and steel. Composite materials could therefore represent a next step for EHV (extra high voltage, e.g. 300 kV – 750 kV) AC overhead transmission lines, perhaps offering solutions that could make overhead transmission lines seem less invasive in the environment in which they are placed. These solutions could either be fully based on overhead lines or in part together with conventional components.

With this in mind a research collaboration between the Danish Transmission System Operator Energinet.dk and Electric Components, DTU Electrical Engineering were established to investigate the future for overhead line systems based on composite materials.

1.1 Background

The PhD project was started early 2006 as a part of the Danish transmission system operator Energinet.dk's strategy on minimising the environmental impact of overhead line systems. Energinet.dk's Strategy Plan states that minimising the environmental impact of overhead line systems is to be achieved by actively developing new technical solutions for transmission lines that are environmentally friendly with special emphasis on new visually less dominating tower types [1].

The aim of reducing the environmental impact of overhead lines in Denmark is an attempt to meet the demands from the general public that overhead lines should be less dominating in the Danish landscape if not made as underground cables.

In 2008 the Danish Electricity Infrastructure Committee published its findings concerning cabling of the Danish transmission grid in the report "Technical report on the future expansion and undergrounding of the electricity transmission grid" [2]. Here six future tracks for the Danish transmission system – ranging from full cabling and undergrounding of the transmission system to keeping the grid in its present state – was presented to be discussed by the Parliament.

The conclusions of the Report are that increased undergrounding of the 400 kV system (currently approximately 10 % is underground cables) present a major technical challenge and cannot be achieved with the present technology. Instead it is suggested in the report that future expansions of the Danish 400 kV grid is accompanied with replacement of existing lattice steel towers of overhead lines with new lower towers, which could be made by use of fibre reinforced composite materials. Expansions of the existing grid could, so to say, be accompanied by projects that improve the visual appearance of the existing as well expansions of the Danish transmission grid [2].

The Danish Electricity Infrastructure Report shows the continued need for the development of overhead line systems with less environmental – especially visually – impact to ensure an alternative to the present overhead line solutions as long as cabling continues to be more expensive and electrically problematic compared to overhead lines.

1.2 Aim

The aim of the PhD project and the present PhD Thesis is to examine the possibilities, the limitations and potential risks of widespread use of composite materials in composite based EHV AC overhead transmission lines. This is with main focus on the electrical aspects of composite materials in overhead line system however also mechanical and thermal aspects are included.

Furthermore it is the aim of the present Thesis to present a design basis for future overhead transmission lines based on composite materials.

1.3 Delimitation

The present PhD Thesis is limited to composite materials that are reinforced with fibres of some length, either in the form of mats or long fibres in components applied at extra high voltage (EHV) levels. The Thesis does not treat mechanics of composite materials in depth but is instead limited to simple consideration illustrating the general mechanical possibilities with composite materials.

The topic of the Thesis is composite materials in overhead lines, however the thesis will not touch on all subjects connected to overhead lines. One of the most publicly discussed of the subjects which are not included in the present work, is electromagnetic fields (EMF) generated by overhead lines. Other areas that are not treated here are audible and radio noise caused by overhead lines.

Aspects such as route selection or other means to reduced the visual impacts of overhead lines are not included in the Thesis either, nor is the economical aspects of the use of composite materials as these cannot be fully predicted based on the available information.

1.4 Outline

The present Thesis is divided into seven chapters (besides the Introduction), which covers the topic of the PhD Thesis.

Chapter 2: In the chapter a selection of different projects aimed at reducing environmental impact of overhead line are presented. Based on these an analysis is made of which tools can be used to reduced the environmental impact with subsequent presentation of different design ideas for composite based overhead line systems at EHV.

Chapter 3: Composite materials are presented in general terms including properties for fibre, matrices and bulk composite materials. Included in the chapter is also a selection of production method for composite materials along with general comments on joining and repairing of composite materials.

Chapter 4: Application of composite materials in overhead line components is described in chapter 4 along with characteristics and properties of a selection of insulators, conductors and towers based on composite materials.

Chapter 5: The chapter deals with the different types of ageing mechanisms that composite overhead line components can be subjected to as well as general failure modes of the composite components. Recommendation on how to limit ageing is presented based on experiences and recommendations gathered from the available literature.

Chapter 6: Describes the electrical and mechanical dimensioning of overhead line systems based on available standards and guidelines. The chapter is concluded with analysis of composite conductor sag-temperature relationships, as well as the need for electrical clearances and mechanical strengths of EHV systems.

Chapter 7: Consists of general power system considerations when introducing composite materials in overhead line systems. Discussion of design ideas presented in chapter 2 based on the information in chapter 3 through 6. Information on the possibilities, limitations and risks of composite based components. Furthermore the chapter points out areas that needs further research in respect to composite based EHV AC overhead line systems.

Chapter 8: The conclusion of the present Thesis.

Chapter 2

Design Ideas for Overhead Line Systems using Composite Materials

The intent with the present Thesis is to investigate which possibilities and – as a natural consequence – limitations that composite materials present for the design of EHV AC overhead line systems. Mainly with respect to the electrical aspects of the design but some mechanical issues will also be pursued. The findings of the research project is to be used as a tool for the incorporation of composite materials based components in the Danish power grid, where composite based components represents a better technical choice than conventional components. The term "better technical choice" covers both a visual improvement of the existing transmission grid in Denmark as well as reliability improvements that the use of composite materials may contribute with.

Especially the intent of reducing the visual impact of EHV AC overhead lines or AC transmission lines in Denmark is basis for initiation of the present research project. Therefore in this chapter several different design ideas based on broad use of composite materials are presented.

These designs will form the basis for describing what can be achieve by today's knowledge for application of composite materials in overhead line systems. However in this chapter they are simply ideas and not necessarily possible applications of composite materials. The ideas will here be limited to a low number of designs representing simple replacement of conventional components with available composite components, use of unconventional tower designs and direct change of what should be part of an overhead line system and how the components should be designed.

2.1 Visually Improved Overhead Line Systems

As composite materials are investigated here to form the basis for improvement of the environmental impact with emphasis on the visual impact of overhead line systems, a short review of different design ideas for overhead lines will be presented in the following. This will be done based on selection of different overhead transmission line designs either being pursued or being in use in the northern part of Europe. These projects are presented as representation of overhead lines that aim at lessening the visual impact of overhead lines.

2.1.1 Selected Compact Overhead Line System Projects

Several different tower designs aimed at reducing the visual impact of overhead line systems are introduced here. Besides the ones presented below several other examples can be found. The solutions given below have however been chosen as they give a good picture of the many different solutions. One include a project originally intended to use composite materials as a part of achieving a visual reduction of an overhead transmission line.

2.1.1.1 The Wintrack Project

The Dutch TSO TenneT for a period pursued the idea of a composite based tower design to be applied in the transmission system. The different design ideas with insulating composite material crossarms are shown in figure 2.1.

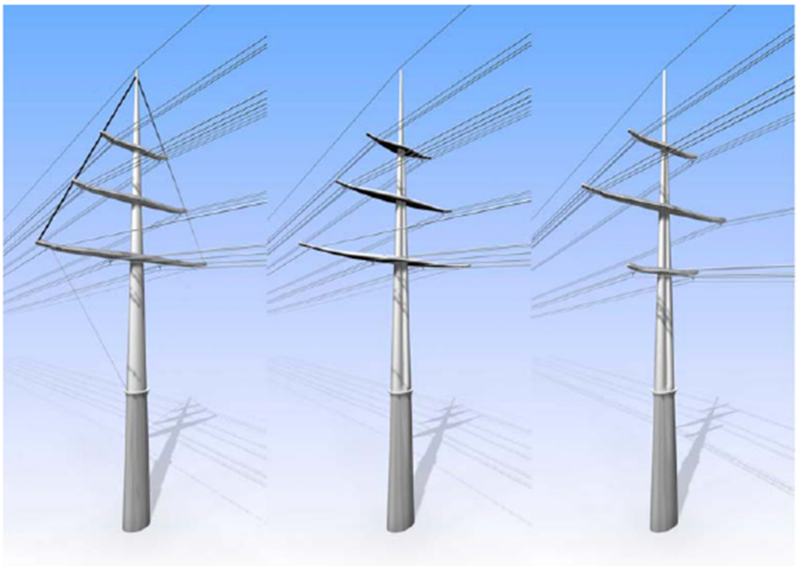


Figure 2.1: Design ideas from the Dutch TSO TenneT's Wintrack project on a composite tower. Design by Movares and TenneT. Courtesy of TenneT.

The three designs are all based on an I-pole tower with insulating crossarms. The crossarms was planned to be made out of an insulating composite material making the use of separated crossarms and insulators redundant and achieving a minimisation of the overhead line system's visual impact. The three variations shown in figure 2.1 are different ideas for how strength and EMF can be optimised.

The composite design was however rejected due to limited time for testing the construction electrically and mechanically, liability issues in the case of failures and doubt concerning the reliability of the insulating crossarms. Instead of the composite based design, a compact design using braced line post insulator and steel pole-towers have been chosen as the solution for the Wintrack project. The arrangement of the conductors have been chosen with respect to minimising the EMF of the transmission line system. The Wintrack design based on steel poles are shown in figure 2.2.

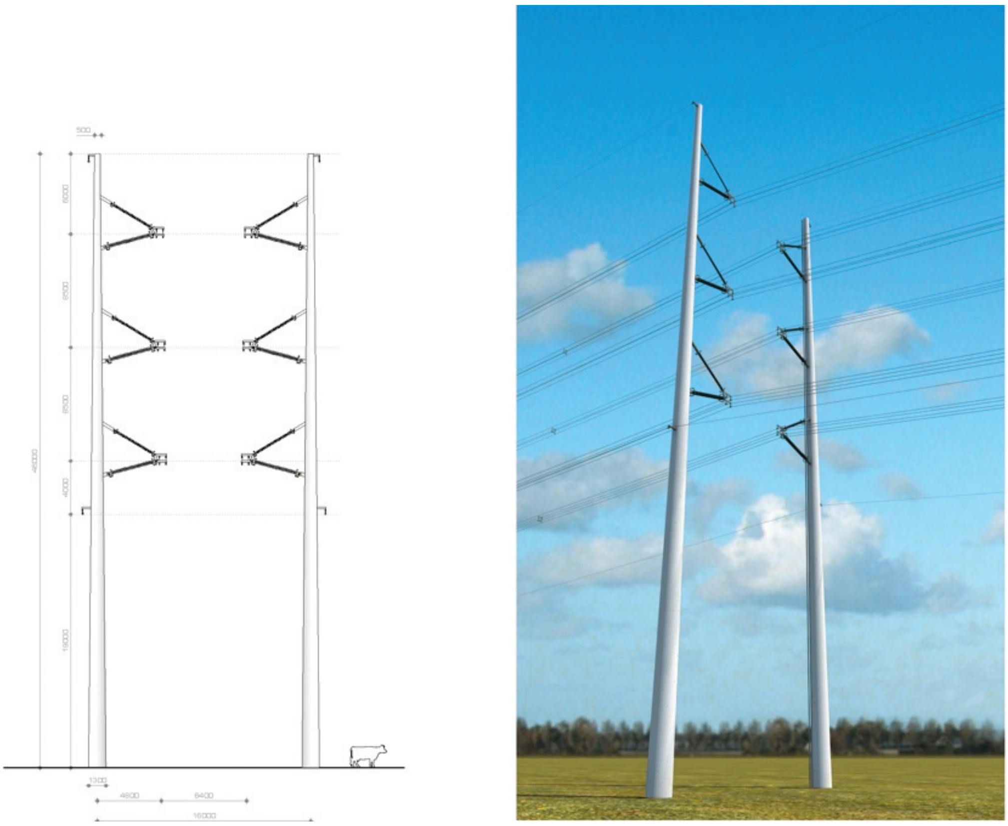


Figure 2.2: The Dutch TSO TenneT's tower design for the Wintrack project. Design by KEMA, Zwarts&Jansma Architecten and TenneT. Courtesy of TenneT.

2.1.1.2 The Compact Plus Tower

Over several years the Norwegian TSO Statnett, the Swedish TSO Svenska Kraftnät, STRI and ABB Switchgear have developed the "Compact Plus Tower". The tower is designed with regard to both limiting the visual impact and the EMF emission of the line by use an optimised compact design.

The most notable difference between the Compact Plus Tower design and normal transmission line system designs are the lack of a ground/shield wires and very close phase spacing. Furthermore instead of ground wires for lightning protection the use of surge arrester in the top phase have been applied. The top phase acts as a ground wire where the connection to earth or conduction of the lightning current to ground is controlled through application of surge arrester in every tower, as seen in figure 2.3 [3].

Figure 2.3: The Compact Plus Tower. Courtesy of Statnett SF.

The design of the tower has gone through several stages, with the latest design shown in figure 2.3. In the design presented in [3] in 1998, normal tension (suspension) units were used for the insulators and each tower was in its own right a dead-end tower. In the design in figure 2.3 composite based hollow core insulators are used. The insulators are mounted directly on a steel tower and the insulators could therefore also be termed as insulating crossarms. Surge arresters are still applied in the top phase, which functions as a shield wire for the other two phases.

2.1.1.3 Svenska Kraftnät's Suburban Tower

The Swedish TSO have developed a tower for application in suburban areas (and the design is therefore referred to as the "Suburban Tower"). The tower has been developed with the aim of reducing the EMF of the line while at the time being aesthetically acceptable. The tower is constructed based on conventional methods with a steel tower, glass insulators and a delta configuration of the conductors to minimise EMF. The tower is shown in figure 2.4.

The tower achieves a reduced visual impact through use of a steel pole tower, close phase arrangement and the use of suspension insulators arranged in a V whereby conductor swing is minimised.

2.1.2 Low Environmental/Visual Impact Design

Based on the projects presented above is possible to drawn some general conclusions on how to reduce the environmental (primarily visual) impact of overhead transmission lines. This is in part done on the basis of figure 2.5 representing the Danube Tower, a lattice steel tower design used Denmark and other countries.

As can be seen from figure 2.5 compared to figures 2.4, 2.2 and 2.3 the tower structure itself represents a big part of the visual impression of the overhead line system. It can be observed that for all the three designs the tower structure is not carried out as a lattice tower but as steel poles. This reduced both the visual impressions of the towers as well as the foot print – the area covered by the tower foot. Examples of concrete towers instead of steel towers can also be found in the literature.

The towers are not the only components of interest however. The arrangement and types of insulators used are also considered in some cases where glass insulators have normally been used. By replacing glass insulators with composite insulators different reductions of the visual impact can be achieved, among these are a slimmer insulator profile and removal of sunlight reflections on the insulators. Furthermore the use of other insulator arrangements can limit conductor swing and allow slimmer structures and/or eliminate the used of normal crossarms, as the insulators functions as the crossarms of the tower. Examples of the use of insulators as a sought of insulating crossarm can be seen in figure 2.2 and 2.3.

For all of the presented designs the phase conductors have generally been brought close to one another by used of phase compaction. This not only alters the visual impact of the line but also reduces the EMF levels of the line. Figure 2.2 is a good example of

Figure 2.4: Svenska Kraftnät's suburban compact tower design. Courtesy of Svenska Kraftnät (Swedish National Grid), photo by Katrin Seuss.

this. However not only the option of moving the conductors carried by the towers closer together exists. Some of the conductors not essential for the transportation of power could also be moved in an attempt to reduce the visual impact. This has been done in the case with the Compact Plus Tower in figure 2.3.

Below is listed the steps taken in the projects presented above to reduce the environmental/visual impact of overhead line systems.

- Going from lattice towers to pole towers
- Use of insulators as crossarms
- Compaction of the phase spacing

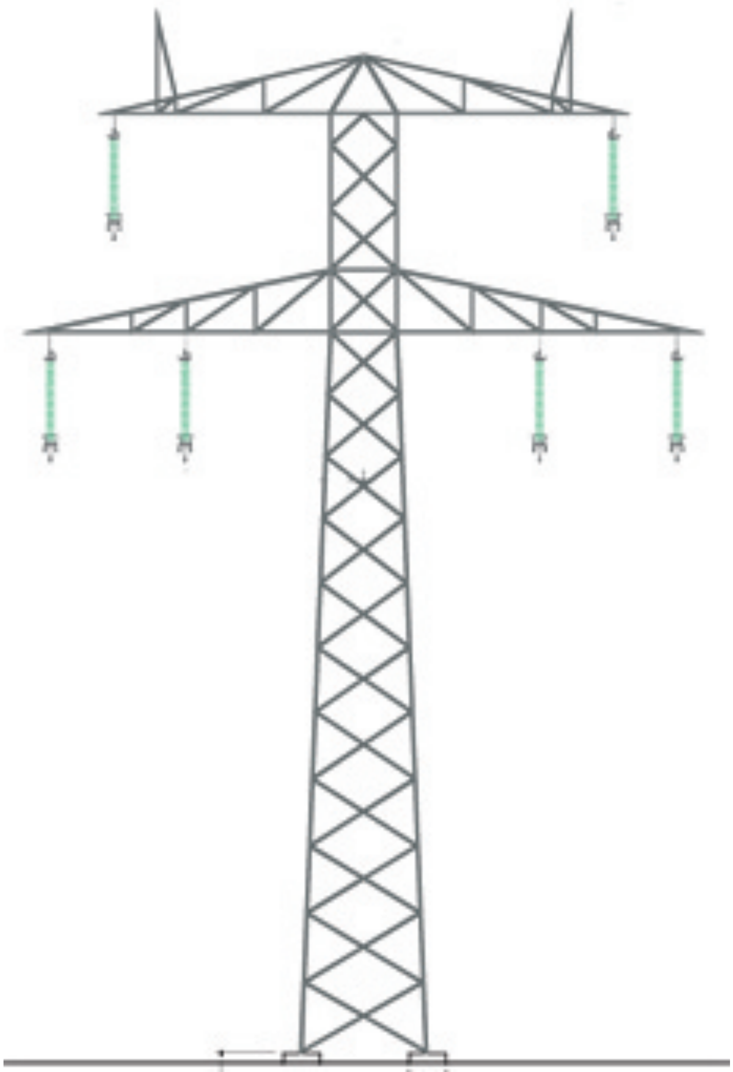


Figure 2.5: A typical example of a Danish EHV overhead line – the Danube tower.

- Removal of ground wires

Besides changing the design of overhead line several other steps can be taken to lessen the visual impact of overhead lines. The Norwegian TSO Statnett makes use of several methods such as painting of the conductor making it blend with the surroundings, treatment of conductors and use of insulator coating or insulator with rubber housing to prevent reflections of sunlight. Camouflaging of overhead lines will be not mentioned further here but should be considered for overhead lines as the mentioned steps are often cheap solutions for reducing the visual impact [4].

In some cases a visual improvement is sought not through reduction of the visual impact as such but by adding an artistic aspect to the overhead line system. Examples of this can be found in plenty in Finland. Here a tradition for unconventional design of overhead line towers have developed where overhead lines are particularly exposed to many people or could seem as particularly imposing on the surrounding environment. The idea is to create a landmark of the overhead line and this is done for one or more towers on a line already clearly visible. A typical point of application is motorway crossings. Examples are shown in figure 2.6.

As a part of the efforts of trying to lower the visual impact of overhead lines, it has in cases also been necessary to try to quantify the visual impact of actual designs. An approach to this is presented in [6].

Other ways of decreasing the visual impact of overhead lines is to choose a line routing where the overhead line system does not break or contrast too much in relation to the environment. Cigré has published a guide on this topic [7] and some examples of route selection to reduce the visual (included in environmental) impact can be found in literature [8]. As stated previously, line routing is not a part of the present Thesis as this is not connected to the choice of materials used for the overhead line system.

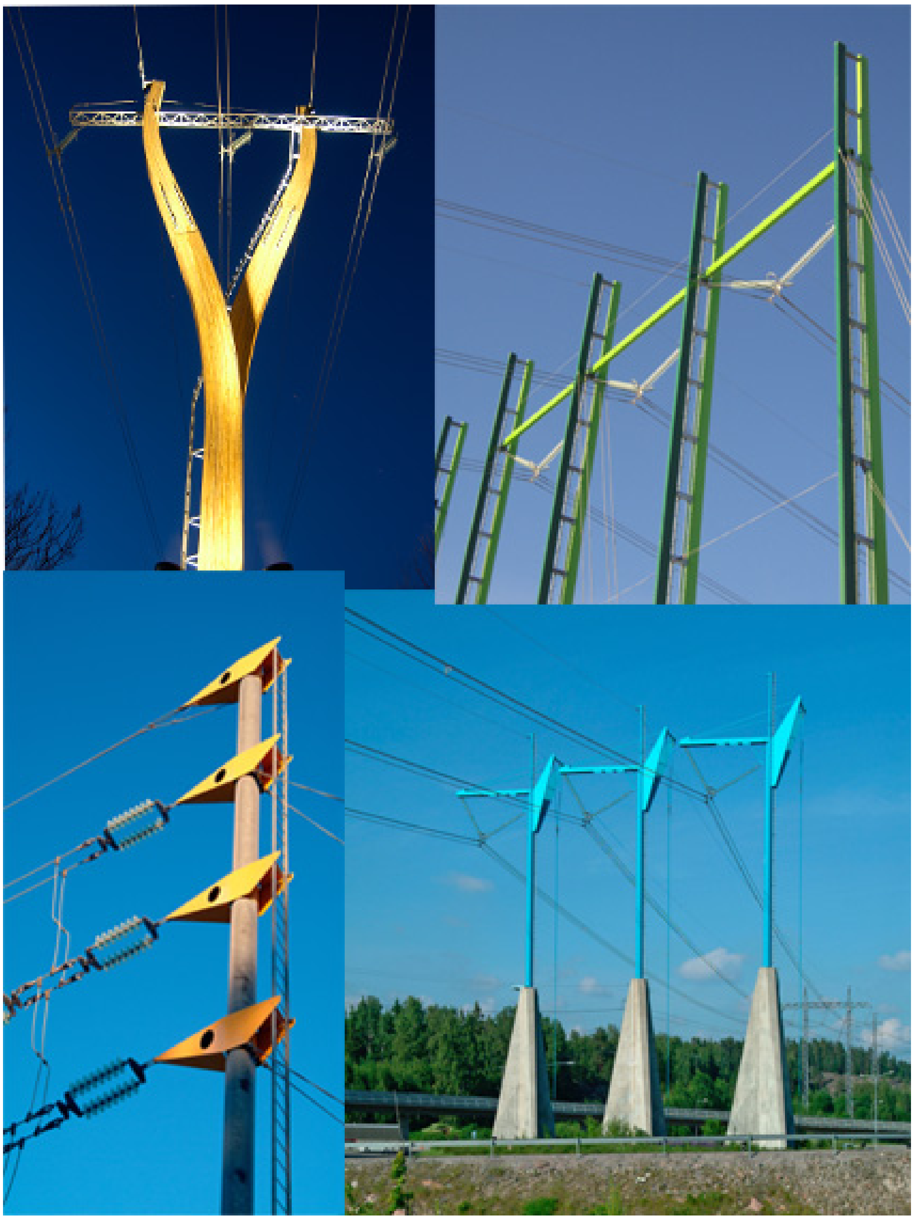


Figure 2.6: Examples of overhead line tower designs in Finland – "non"-low visual impact towers [5]. © Fingrid Oyj.

2.2 Designs based on Available Composite Based Components

Simple designs based on available components based on composite materials are presented in the following. These are more or less conventional design approaches and can in-part be found in the transmission systems of the present.

An EHV AC overhead transmission line system, and for that sake any other overhead line system, consist of a tower carrying conductors by using insulators as the connection medium. Tower, insulators and conductors are separate components combined to form the overhead line system. See more in chapter 4.

2.2.1 I-pole Without Crossarms

A design based on composite components which might be achievable by today's commercial components can be based on an I-tower made either from a fibreglass like material or concrete reinforced with fibre rods. At the tower top either composite based post insulators or horizontal V-insulator sets can be mounted for carrying the conductors of the system. This should present a low visual impact overhead line system. The conductors should be commercially available composite conductors utilising a composite core as the mechanical support. The use of composite based conductors can lead to better sag characteristics of the conductors making it possible to lower the height of the system as well the distance between conductors mounted above one another.

Based on whether or not ground wires needs to be used, the line can have several different designs as the need for connection points of the ground wires to the tower can have a great influence on the chosen composition. Examples of how an I-pole with post insulators or horizontal V-insulator sets can look are given in figures 2.7 and 2.8.

2.2.2 Y-tower

A composite based overhead line system based on a Y-tower in composite materials is presented in the following. The tower is Y-shaped, where the crossarms makes up the arms of the Y. The tower structure including crossarms is made in a mechanically strong composite material construction. The joining of the arms to the tower base must be considered as a critical mechanical point. The tower can equipped with either one composite suspension insulator per phase or by two in a V-chain per phase. The use of V-insulator set would limit the swing of the conductors. The number of phases could either be three or six, with six offering the most symmetrical alternative. Composite based conductors can be applied to reduce the sag profile of the conductors are thereby reduce the overall height of the system. Concept sketches are presented in figure 2.9 and 2.10.

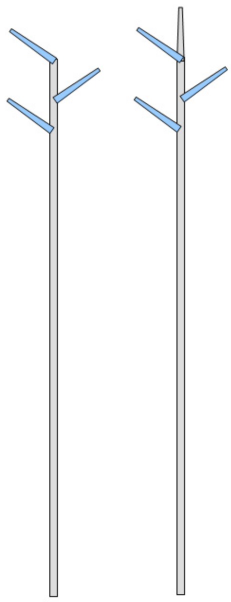


Figure 2.7: Composite based I-pole with post insulators. If a ground wires must be used, the tower can be elongated for the attachment of a ground wire protecting the phases of the system (right part of figure).

For both design ideas the use of ground wires does not have much effect on the design. With ground wires it is necessary to arrange for mounting point of the ground wire(s) and connecting the ground wire to earth where necessary through a down-conductor running either externally or internally on the tower.

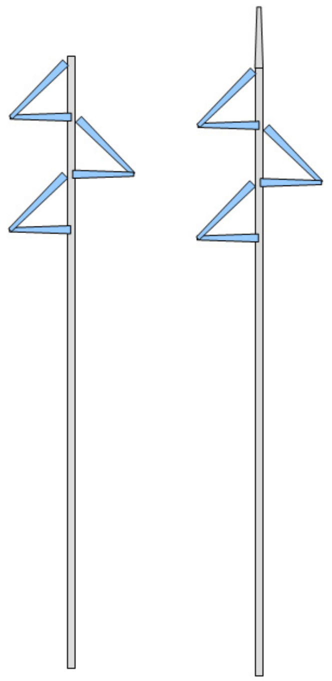


Figure 2.8: Composite based I-pole with horizontal V-insulator sets. If a ground wires must be used, the tower can be elongated for the attachment of a ground wire protecting the phases of the system (right part of figure).

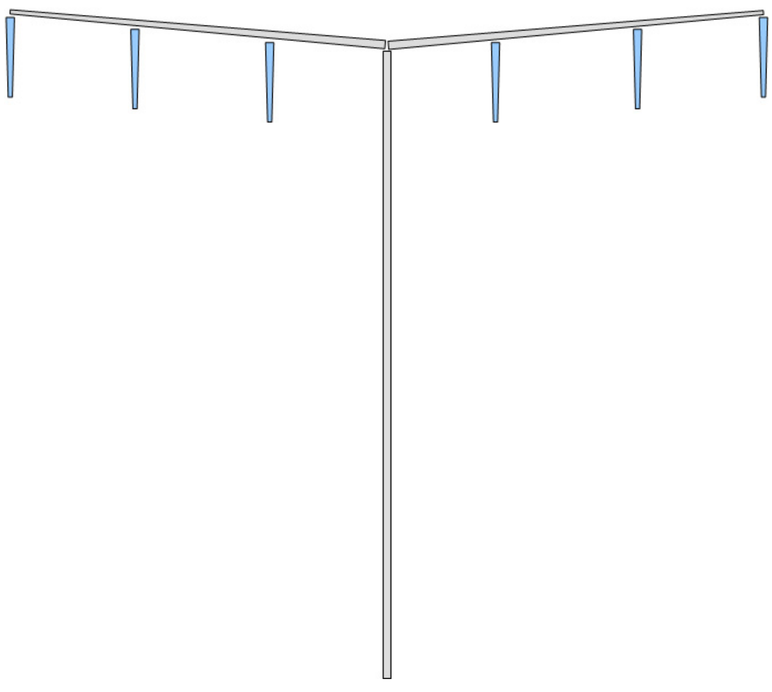


Figure 2.9: Composite based Y-tower with suspension insulators.

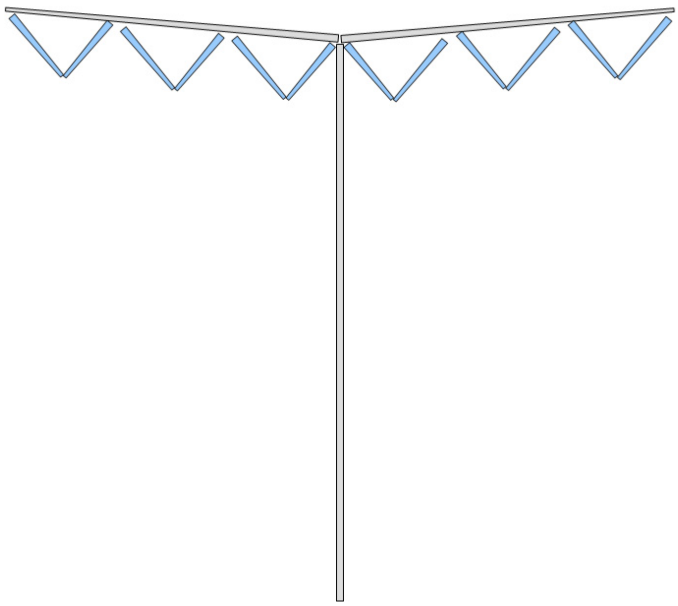


Figure 2.10: Composite based Y-tower with V-insulator sets.

2.3 Unconventional Design Ideas

Some of the composite materials being considered in the present Thesis are insulating while others are not. Fibreglass, one of the most used composites, is an insulator and used in many applications including larger mechanical constructions. From this was born the idea to combine the mechanical tower structure and the insulating characteristics of insulators into one structure either as a tower with an insulating tower top or as a tower which at the same time functions as an insulator. This has to some degree already been achieved by use of horizontal V-insulator sets or post insulators whereby the insulator sets function as the tower crossarms thereby forming an insulating crossarm. In the following this idea will be expanded to combine the insulators and the mechanical tower construction.

2.3.1 Y-tower with insulators integrated in tower top

In April 2008 the “Fibre Tower” – a tower concept design based completely on composite materials – was for the first time publicly presented in the Danish Electricity Infrastructure Report [2, 9]. This tower represents a use of composite materials for overhead line systems not yet seen in application around the world. The tower is represented in figure 2.11.

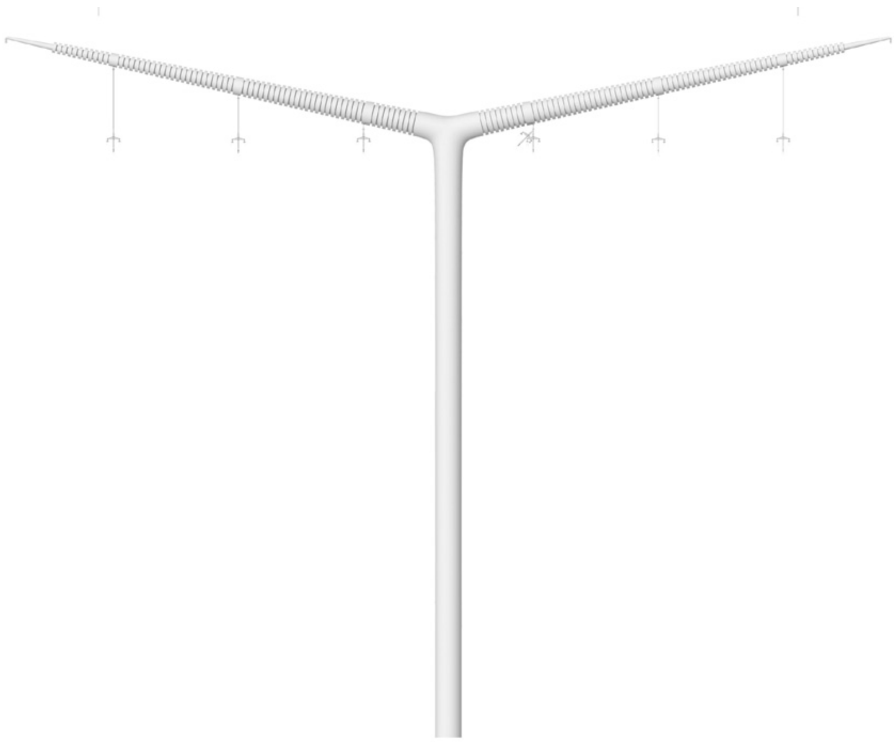


Figure 2.11: Energinet.dk’s “Fibre Tower” (concept design by Bystrup Arkitekter) [2].

An overhead line system based on the “Fibre Tower” can exist in two versions. One where ground wires are utilised as is the standard on overhead line systems on transmission level or without ground wires though equipped with lightning overvoltage protection equipment.

The reason for considering a version of the tower without use of ground wires is to limit the space taken up by the conductors and ground wires in the air space between towers. The idea is that through exclusion of the ground wires a visual reduction of the overhead line system as a whole will be achieved.

The tower itself consists of a tower pole made from a mechanically strong composite material suited for the purpose, e.g. fibreglass. The composite pole carries the tower top which consists of a joint connecting the crossarms to the tower pole. The joining of the different components will most likely have to be done by use of metal flanges to ensure the mechanical integrity. The crossarms are tubular and made from fibreglass (or another insulating composite material) covered by a rubber housing designed for good pollution flashover performance where the fibreglass cannot suffice. An example of the insulator housing design is shown in figure 2.12. If ground wires are used, these can be connected at or near to the end of the crossarms. However this would need further research to ensure a good performance.

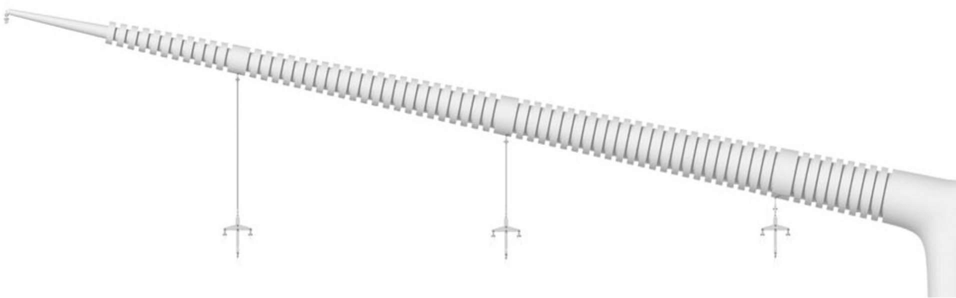


Figure 2.12: Close up of insulation housing on “Fibre Tower” (concept design)

Already at this stage mechanical and electrical engineers will form ideas of how the design could be realised but also several areas of challenge will stand out. How to realise the design and point out where the greatest challenges in the design are, is the intention with the following chapters on Composite Components Exposed to Electrical, Mechanical, Thermal and Environmental Effects in Overhead Line Systems and Dimensioning.

Conventionally ground or shield wires have been used to shield overhead lines from lightning strokes to the phases as lightning can lead to severe transients in the system. These transients can either lead to flashover of the line insulators and/or damages to equipment either in the overhead line system or in substations connected to the line. Especially the equipment in substations can lead to costly faults.

With composite structures there is however a question concerning whether ground wires can be connected to ground to ensure an acceptable performance and limit the voltage amplitude of the resulting overvoltages. Compared to steel, the composite materials typically used for towers are not conductive and can therefore not be used as connection for ground wires to the earth.

Alternatively introduction of a down-conductor along the tower structure could be made, either as a bare conductor or a cable. Other alternatives could be large jumpers bypassing the insulation between the ground wires and ground [9].

Chapter 3

Composite Materials

The term composite material can cover many and very different materials in everyday speech. Examples are fibreglass, plywood (laminate) or reinforced concrete to name a few. These are all composite materials in the broader sense and many others materials can be added to the list.

Composite materials are today used in many applications and within many different areas of construction. One of the most well-known usages is for wind turbines blades. Less known usages are perhaps use of composite materials for great parts of aeroplane constructions (50 % of the Boing 787 Dreamliner main construction will be composite materials [10]) and panelling for buses and cars. Also bridges and beds for MR scanners are applications where composite materials are used. For a more comprehensive list, refer to [11].

A definition of composite materials can be found on Wikipedia [12] and is reproduced below.

> "*Composite materials (. . .) are engineered materials made from two or more constituent materials with significantly different physical or chemical properties which remain separate and distinct on a macroscopic level within the finished structure.*"
>
> Wikipedia [12]

As can be seen from the quote above, composite materials can cover many different materials. In the present thesis, composite materials of interest are limited to fibre-reinforced composite materials.

3.1 Introduction to Fibre-reinforced Composite Materials

Fibre-reinforced composite materials are materials that consist of fibres embedded in a matrix. Typically the matrix is weaker in mechanical strength than the embedded fibres but the matrix acts as the binder between the fibres and a load transmitter to the fibres. The binding between the fibres and the matrix are established during the manufacturing of the composite material. Besides the two main components, fibres and matrix, also additives and coatings can be relevant when discussing fibre-reinforced composite materials [11, 13].

3.1.1 Fibers

The fibres contribute with their strength to the composite materials. However how and how much the fibres contribute to the final properties of the final composite material is dependent on several factors.

The length of the fibres is one very important factor. The fibres can either be used in the form of mats, felts or short fibres in injection moulding. The length of the fibres used for these applications varies from a few centimetres to millimetres and are thus generally referred to as short fibres. Longer fibres are used for application where continuous fibres or large weaves of fibres are needed. The length of the fibres is controlled during the manufacturing of the composite material as the fibres are delivered on rolls with up to several hundred metres of fibres per roll. Whether the fibres are continuous or discontinuous is thus important.

Another factor that influences the properties of the final composite material is the orientation of the fibres. Fibres in composite materials can be unidirectional, bidirectional or tri-directional. Composite materials are anisotropic which means that the direction of the fibres determines the final properties of the composite material. However in the case of tri-directional short fibres the bulk material could end up being isotropic. Unidirectional fibres are in example used for composite material beams to ensure a high tensile strength and stiffness in the axial direction of the beam. Bidirectional solutions are among other things used for wind turbine blades to ensure good properties both in the axial and radial directions of the blade [11, 14].

Some of the most common fibres in composite materials for the construction and high voltage industry are presented in the following. An overview of the properties of the fibres are presented in table 3.1 in section 3.1.1.5.

3.1.1.1 E-Glass

E-glass or electrical glass is the most common form of glass fibres used. E-glass has good tensile and compressive strength and is an electrical insulator (high dielectric strength). However E-glass has poor impact resistance.

Glass fibres are produced by leading liquid glass through micro fine bushings under cooling. The glass filaments are then drawn into strands which are further treated to ensure the stability of the fibres [13, 14].

3.1.1.2 E-CR-Glass (C-glass)

C-glass and E-CR-glass is a modified version of E-glass that ensures good chemical resistance of the glass fibres by use of a different composition for the glass. C-glass, in spite of its good chemical resistance, has a weakness to acids formed under wet conditions. To enhance the resistant to acids of C-glass, the boron content is removed from the C-glass thus producing E-CR-glass (boron-free glass fibres). Both C- and E-CR-glass are often used in surface layers and for chemical and water pipes and tanks. Both C- and E-CR-glass are also used for overhead line insulators cores, to make the insulators resistant or immune to brittle fracture (more in chapter 5).

Other versions of glass fibres are R-, S- and T-glass which are typically high strength glass fibres. These are more expensive than E-glass (approximately 10 times as expensive) and are therefore only used for special applications. Properties of these special fibres are not included in table 3.1 [13, 14].

3.1.1.3 Carbon

Carbon fibres are created through controlled oxidation, carbonisation and graphitisation of carbon-rich organic precursor in fibre form. The process leads to high strength or high modulus carbon fibres. Carbon fibres are commonly grouped after their strength and elasticity modulus in the groups; HS (high strength), IM (intermediate modulus), HM (high modulus) and UHM (ultra high modulus).

Carbon fibres have very high tensile and compression strength and have lower density compared to glass fibres. Furthermore they are resistant to corrosion, creep and fatigue. As with glass fibres however they have a low impact strength which is even lower than for glass fibres [13, 14].

3.1.1.4 Aluminium Oxide

Aluminium oxide (Al_2O_3 or Alumina) fibres is the most used oxide ceramic materials. Aluminium oxide is most often found in powder form and is used in spark plugs, cutting tools and electrical burners. Aluminium oxide fibres exhibit high compression strength and good chemical resistance. Furthermore aluminium oxide is an insulator and has a high dielectric strength. Aluminium exposed to oxygen will form a fine layer of aluminium oxide on its surface, this is the reason why aluminium used in electrical systems needs to be polish before joining to ensure good electrical contact [15, 16].

3.1.1.5 Overview: Properties of Fibres

In table 3.1 electrical, mechanical and thermal properties of the above mentioned fibres are listed.

From table 3.1 it can be seen that carbon fibres are the lightest, strongest and stiffest of the represented fibres. Carbon fibres have very low thermal expansion compared to the other fibres and can be used at high temperatures.

The aluminium oxide fibres have a high stiffness comparable to HM carbon fibres, but a density twice as high. The aluminium oxide fibres can also be used at relatively high temperatures but are however weaker than both glass and carbon fibres. The Al_2O_3 fibres are superior when it comes to sheer modulus.

The carbon fibres are electrical conductive whereas the Al_2O_3 and glass fibres are insulators. The withstand strength of Al_2O_3 are higher than for the glass fibres. The dielectric constants are also quite different for the two materials.

3.1.2 Matrix

The matrix material ensures the bonding of the fibres in the finished bulk composite material and the transfer of loading to the fibres. Many different materials can be used for the matrix of composite materials. The three main groups of matrixes are polymeric, mineral and metallic matrixes. Properties of the below mentioned matrix materials are listed in table 3.2.

3.1.2.1 Polymeric Matrix

Polymeric matrixes are divided into two groups; thermosets and thermoplastics. The thermoset resins cover polymers that cannot melt whereas thermoplastic resins are polymers that can melt.

Some of the most used polymeric matrixes are polyester, vinylester and epoxy which are often used in combination with glass fibres. These all belong in the thermoset group. Some of the advantages of using epoxies are in example that they polymerise without condensation, there is little shrinkage during curing which reduces internal mechanical stresses and they are chemically resistant.

Table 3.1: Mechanical, electrical and thermal properties of selected fibres [11, 13, 14, 17, 18, 19, 20].

Mechanical properties

	Fibre diameter (μm)	Density (kg/m^3)	E-modulus (GPa)	Shear modulus (GPa)	Poisson ratio	Tensile strength (MPa)	Elongation (breakage point) (%)	Useful temperature limit (°C)
E-glass	16	2600	74	30	3.5	2500	3.5	700
E-CR-glass		2700	73			3200		
HS Carbon	7	1750	230	50	0.3	3500-5300	1.3	>1500
HM Carbon	6.5	1800	340-390	20	0.35	2500-4800	0.6	>1500
Al_2O_3		3950-4100	380	150	0.22	1400		1700

Electrical and thermal properties

	Dielectric constant	Volume resistivity Ohm·cm	Surface resistivity Ohm·cm	Withstand voltage kV/mm	Coefficient of thermal expansion (10^{-5}°C)	Heat capacity (J/kg°)	Thermal conductivity W/mK	Flammability
E-glass	6.4	10^{14} - 10^{15}	10^{13} - 10^{14}	8-12	0.5	800	1	Non-flam.
E-CR-glass					0.59			Non-flam.
HS Carbon					0.02	800		
HM Carbon		0.0016			0.08	800		
Al_2O_3	9.8	$> 10^{14}$		17	0.8	850-900	35	

An examples of thermoplastics is nylon (often used with carbon fibres) which turns to liquid when heated. The general advantages of thermoplastics compared to thermosets are low production costs, improved toughness, improved impact resistance and low moisture uptake [13, 21, 22].

3.1.2.2 Mineral Matrix

Mineral based matrixes cover silicon carbides and carbon. In these applications the composite consists of matrix and fibres of the same material. They are often used for high temperature applications such as brake disks and space craft plating (re-entry body) [11].

3.1.2.3 Metallic Matrix

Metallic matrixes cover different metal alloys that are used as the matrix for composite materials. The most used metallic matrixes are light weight metals such as aluminium and titanium. Different type of fibres can be used as reinforcement both metals and non-metals however alumina (Al_2O_3) and silicon carbide is commonly used. The advantages of using a metallic matrix instead of in example a polymeric matrix are that metals have significantly greater strength, stiffness and that they can potentially be applied at higher temperatures [11, 13, 23].

3.1.2.4 Overview: Properties of Matrixes

Properties for the most common polymeric, mineral and metal matrix materials are presented in table 3.2.

One of the most notable differences between the different matrixes is the high values of density and elasticity modulus of aluminium. Aluminium also has a high thermal expansion coefficient and thus has very different properties than the other matrix materials.

Generally the other matrix materials have very similar properties though epoxy shows slightly greater tensile strength than the other materials.

Compared to the fibres the following should be noted; the matrixes generally allow greater elongation before breaking, the matrixes have higher temperature thermal expansion coefficients, which can lead to internal tensions in the composite materials at high temperature. Furthermore some of the matrixes are limited to lower temperature ranges than the fibres with respect to application.

Table 3.2: Mechanical, electrical and thermal properties of selected matrixes [13, 14].

	Density (kg/m^3)	E-modulus (MPa)	Shear modulus (MPa)	Poisson ratio	Tensile strength (MPa)	Elongation (Breakage point) (%)	Thermal Expansion Coefficient (10^{-5}°C)	Heat capacity (J/kg°C)	Useful temperature limit (°C)
Polyester	1200	4000	1400	0.4	80	2.5	8	1400	60-200
Vinylester	1150	3300			75	4	5		>100
Epoxy	1200	4500	1600	0.4	130	2 – 6*	11	1000	90 – 200
Polycarbonate	1200	2400		0.35	60		6	1200	120
Polyurethane	1100	700-7000		30	100		100		
Silicone	1100	2200		0.5	35				100 – 350
Aluminium	2710	69000	26000	0.33	74		23.6		

* Epoxy elongation is very dependent on temperature. The values apply at 100 °C and 200 °C respectively

3.1.3 Additives

Additives are (commonly) added under the manufacturing process of the composite material. These can be something as simple as fillers to lower the cost or colour of the finished composite material. Fillers can also be added to change or enhance the composite materials properties. Examples are to increase the UV-stability or change the electrical properties of the composite material. The use of additives will not be covered here as the result of different additives mixtures are often hard to predict and the additive ratios are in many cases trade secrets.

3.2 Production Methods

Composite materials are manufactured in several different ways. Which method to use is dependent upon the demands to the manufactured composite material, which fibres and matrix are used, the costs and size of the final composite material subject. Some of the different approaches to manufacturing composite materials are presented in the following sections. For additional processes [11, 14] can be consulted.

Lay-up

Spray or Hand lay-up (also called contact moulding) is properly one of the best known approaches to manufacturing composite subjects. The fibers impregnated with resin (the matrix) are laid in a mould and more resin can be added by a hand-tool of spray gun before the layers are pressed together by a roller. This can be repeated several times until the wanted thickness of the composite material is reached. Afterwards the composite material is left to cure in the mould [11, 13, 14].

Compressive

Compressive moulding is similar to contact moulding described above except that pressure is applied by a top mould under low pressure [11, 13].

Vacuum Bagging

With vacuum moulding the impregnated fibres are places in an open top mould. When the fibres are laid out the mould is topped with a thin plastic, a bag or a mould and vacuum is applied. Pressure is thus applied to the subject by the surrounding atmospheric pressure. Air bubbles are sucked from the subject due to the vacuum. Afterwards the subject is set to cure at elevated temperature in an oven. The process can also be performed in an autoclave where subject is under high pressure.

Vacuum bagging is used extensively for the fabrication of wings for wind turbines [11, 13, 14].

Injection Moulding

With injection moulding the resin is injected under low pressure between a mould and a counter mould where the fibres have been arranged beforehand. This is also referred to as the resin transfer moulding [14].

Injection moulding can also be used where the fibres are premixed into the matrix. Fibres and matrix is the injected into mould. The mixture is either heated before injection or while in the mould depending on the matrix type [11, 13].

Filament Winding

Filament winding is a process where fibres a draw through a resin bath and then wound onto a mandrel or tube mould. The direction of the fibres can be changed during the process which can make continuous lengths of tube, pipe or tanks [11, 13, 14].

Pultrusion

Fibres from reels (up to hundreds at a time) are guided through a heated die where they are impregnated with a matrix and shaped to a wanted cross section. The process is continuous and cut-offs in appropriate sizes can be made. With some changes to the setup, small variations in the cross section can be made during the casting process. Pultrusion is often used for the manufacturing of panels and construction elements [11, 13, 14].

3.3 Properties of Fibre-reinforced Composite Materials

The properties of a composite material are dependent upon the materials used for the fibre and matrix, the ratio in which the two (or more) components are applied to one another and the orientation of the fibres in the material.

The volume fraction of the fibre and matrix is directly related to the final composite materials properties. The volume fraction is calculated as the ratio between the fibre volume or matrix volume in relation to the total volume of the composite material as given in equation 3.1 and 3.2.

$$V_f = \frac{\text{Volume of fibre}}{\text{Total volume}} \tag{3.1}$$

$$V_m = \frac{\text{Volume of matrix}}{\text{Total volume}} \tag{3.2}$$

Other important factors for the properties of the finished composite material are the number of plies and the orientation of each ply in relation to the load(s) on the composite material. This applies both for mechanical and electrical loads [11, 13].

3.3.1 Mechanical Properties of a Unidirectional Ply

For a unidirectional ply the mechanical properties can be determined based on the fibre and matrix properties. This applies for the modulus of elasticity, shear modules and Poission coefficient. For composite materials of multiple plies with different orientations the process becomes slightly more complicated. For multiple plies the number of layers and the direction of each individual layer must be known to calculate the full properties of the composite material. The equations behind multiple plies also called laminates is not presented here but are however very interesting in applications where forces of multiple directions must be handled by the composite materials [11, 13].

Composite materials reinforced with long fibres are usually anisotropic materials. This means that the reaction of the material is dependent on the orientation of the load in relation to the material. For a composite material the elasticity modulus is highest in the direction in the fibre direction and lowest perpendicular to the fibres.

The relation between the elongations of a composite material in the direction of the fibres, ε_l, elongation perpendicular to the fibres, E_t, and the shear strain, γ_{lt}, to the stresses on the composite material in the directions of the fibre and perpendicular to the fibres, σ_l and σ_t respectively, and the shearing stress, τ_{lt}, are described by equation (3.3).

$$\left\{ \begin{array}{c} \varepsilon_l \\ \varepsilon_t \\ \gamma_{lt} \end{array} \right\} = \begin{bmatrix} \dfrac{1}{E_l} & -\dfrac{\nu_{tl}}{E_t} & 0 \\ -\dfrac{\nu_{lt}}{E_l} & \dfrac{1}{E_t} & 0 \\ 0 & 0 & \dfrac{1}{G_{lt}} \end{bmatrix} \left\{ \begin{array}{c} \sigma_l \\ \sigma_t \\ \tau_{lt} \end{array} \right\} \tag{3.3}$$

The relationship of the strains and shear strain to the stresses and the shearing stress is dependent on the elasticity modulus along the length of the fibres and in the transverse direction to the fibres, E_l and E_t respectively, the Poisson ratio, ν_{lt}, and the shear modulus,

G_{lt}. It is here the assumption that stresses are only applied in the l, t-plane and that the composite material is elastic.

Often the fibres and the directions of the forces are not aligned in which case the relation above must be transferred from the l, t-plane to an arbitrary x, y-plane rotated by angle, α. The transformation from the l, t-plane to the x, y-plane is thoroughly described in textbooks and will not be presented here.

For the isotropic case the modulus, E, Poisson ratio, ν, and shear modulus, G, become independent on the direction of the loads on the composite materials. Thus $E = E_l = E_t$, $\nu = \nu_{lt} = \nu_{tl}$ and $G = G_{lt}$ and the following relation apply $G = \frac{E}{2(1+\nu)}$.

For the anisotropic cases the modulus, Poisson ratios and shear modulus are dependent on the fibre and matrix volume fractions as described below [11, 13, 24].

3.3.1.1 Modulus of elasticity

The modulus of elasticity along the fibre direction, E_l, can be determined from the modulus of elasticity of the fibre, E_f, and modulus of elasticity of the matrix, E_m.

$$E_l = E_f V_f + E_m V_m \tag{3.4}$$

In the transverse direction of the fibres, the transverse modulus of elasticity of the fibre, E_{ft}, must be used to determine the modules of elasticity in the transverse direction E_t.

$$E_t = E_m \frac{1}{V_m + \frac{E_m}{E_{ft} V_f}} \tag{3.5}$$

3.3.1.2 Shear Modulus

The shear modulus, G_{lt}, which describes the relation between shearing stress and shear strain, can be calculated from the shear modulus of the matrix, G_m, and the shear modulus of the fibres, G_{flt}.

$$G_{lt} = G_m \frac{1}{V_m + \frac{G_m}{G_{flt}} V_f} \tag{3.6}$$

For the matrix and the fibres the shear modulus can be calculated based on the elasticity modulus and Poisson ratio.

$$G = \frac{E}{2(1+\nu)} \tag{3.7}$$

3.3.1.3 Poisson Coefficient

Finally the Poisson coefficient can be calculated from the Poisson coefficients of the fibre and matrix, ν_f and ν_m respectively. The Poisson ratio describes the contraction in the transverse direction when a tensile load is applied in the longitudinal direction.

$$\nu_{lt} = \nu_f V_f + \nu_m V_m \tag{3.8}$$

3.3.2 Production Methods Influence on Mechanical Properties

The chosen production method affects the mechanical properties of the final composite material since this will affect the fibre and matrix volume fractions. The materials chosen for the composite material will however also determined which production methods can be used as the different materials will behave differently and need different treatment during the manufacturing of the composite material.

In table 3.3 the fibre volume fractions for selected production methods are listed. It can be seen from equations (3.4) to (3.8) that the fibre volume fraction will play an important part in the final values of the mechanical properties of the composite material.

Table 3.3: Fibre volume fraction dependent on moulding process [11].

Moulding process	Fibre volume fraction
Spray/hand lay-up	30 %
Compression moulding	40 %
Filament winding	60 % – 85 %
Vacuum moulding (bagging)	50 % – 80 %

The mechanical properties of composite materials can be determined for unidirectional plies and laminates by the previous equations. For more complex structures however the only sufficient method to determine the properties of the final composite material is through testing of the material [11].

3.3.2.1 Mechanical Failure of Fibre-reinforced Composite Materials

Fibre-reinforced composite materials have three general modes of failure. These are breakage of the fibres, rupture of the matrix and delamination between the plies of the composite material.

The failures arises due to either tension, compression, bending (tension and compression) and shear forces that can lead to delamination [11].

Unlike metals, a laminate material does not have a plastic domain when loading the material. Metals will have a reversible loading zone where the material is elastic however

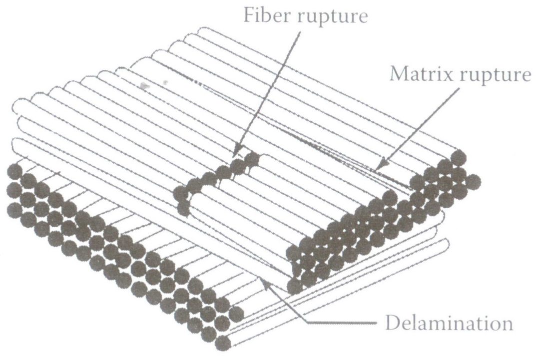


Figure 3.1: Failure modes of laminates [11].

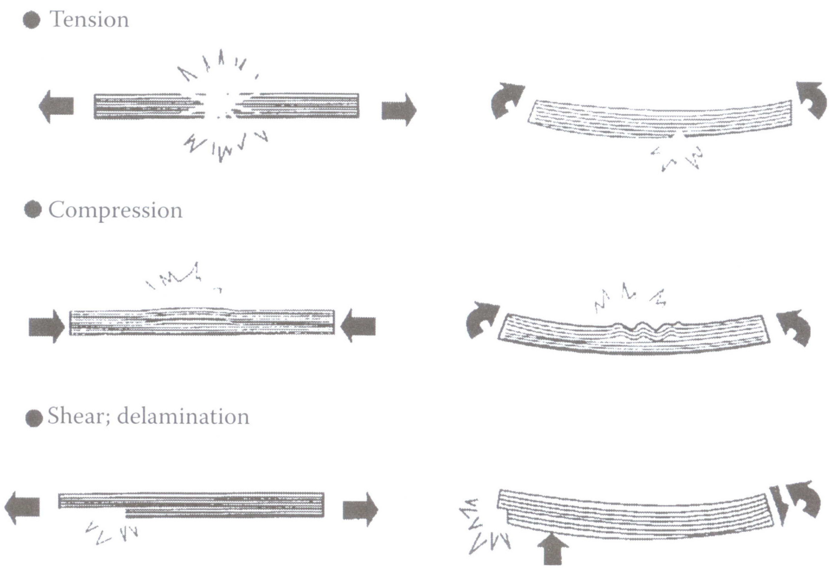


Figure 3.2: Damages to laminates [11].

at the elastic limit the materials will become plastic until the metal fails – fractures. A laminate will on the other hand continue to be elastic until it fractures. However even though the laminate will continue to be elastic it can have fractures of the individual plies before the laminate as a whole will fail. This is irreversible damage but does not lead to immediate failure as the load is distributed to the rest of the laminate. Thus a composite material can have internal mechanical failures without this leading to mechanical failure of the entire composite material [11].

3.3.3 Production Methods Influence on Electrical Properties

With regard to the electrical properties of composite materials the end result can be hard to predict precisely. The electrical properties will in most cases have to be determined through rigourous testing of the composite material and are also dependent on whether or not the composite material is conductive. Furthermore as mention in section 3.1.3 several different additives can be added to the composite material during its manufacturing and several different additives can be used to optimise the electrical properties of the composite material. Thus the determination of the electrical properties of composite materials must be done through testing. It has not been possible to determine how the different production methods influence the electrical properties. An important factor however with regard to the electrical ageing of a composite material is the formation of voids.

3.3.3.1 Electrical Failure of Fibre-reinforced Composite Material Insulators

Voids in a composite material insulator will deteriorate the electrical strength of the material and can lead to internal discharges. Voids can arise in the matrix either between fibres or between fibre layers in the case of laminates during the manufacturing due to air bubbles being enclosed in the composite material when the matrix is applied to the fibres. Processes like vacuum bagging and injection moulding tries to counter this issue by use of vacuum to suck out any air or gas bubbles formed under the matrix application. Depending on the voids orientation in the composite material and relative to the mechanical forces acting on the material the presence of voids can be more or less severe.

3.3.4 Overview: Properties of Composite Materials and Other Selected Materials

Table 3.4 contains an overview of some the composite materials often used for overhead components application based on the fibres and matrixes presented in the previous sections (with overview of fibres in section 3.1.1.5 and matrices in section 3.1.2.4). Also included in the figures are properties for steel, aluminium, concrete and wood for comparison.

The carbon fibre epoxy mixtures are the stiffest and strongest composite materials from table 3.4. These composites are also low in density and have a low thermal expansion. The glass-epoxy composite material is far from as strong or rigid as the carbon-epoxy composite. Glass-epoxy composites are however much cheaper than carbon-epoxy composites and are therefore used much more often. Furthermore the glass-epoxy mixture is an insulator whereas the carbon-epoxy composite is conductive along the length of the carbon fibres.

Comparing the composite materials to steel, aluminium and concrete, some of the most

Table 3.4: Mechanical and thermal properties of selected fibre-reinforced composite materials [11, 13, 24].

	Volume fibre fraction (%)	Density (kg/m^3)	E-modulus (MPa)	Shear modulus (MPa)	Poisson ratio	Tensile strength (MPa)	Elongation – Breakage point (%)	Thermal expansion coefficient (10^{-5} °C)	Heat capacity (J(kg°C)	Useful temperature limit (°)
CF-Epoxy HS	55-70	1500	130,000			1,900		-0.30 – 0.30		
CF-Epoxy HM	55-70	1600	210,000			1,200		-0.60 – -0.25		
Glass-Epoxy	60	2080	45,000	4,500	0.3	1,250		0.4 – 0.7		
Carbon-Epoxy	60	1530	134,000	4,200	0.25	1,270		-0.12		
Al_2O_3-aluminium		3,450	262,000			586				350
Carbon-aluminium		2,370	131,000			455				350
Non-composite										
Steel		7800	205,000	79,000	0.3	400-1600	1.8-10	1.3	400 – 800	800
Aluminium		2800	75,000	29,000	0.3	450	10	2.2	1000	350
Concrete		2200-2400	14,000-41,000	6000-17,000	0.2	2-5			750	
Wood, Pine *		390-500	10-12							

* Based on Shortleaf Pine and Western White Pine, loading parallel to the grain.

used construction materials (among others in OHLS), it can be seen from table 3.4 that the composite materials are generally of lower density but at the same time have comparable elasticity modulus and the same or higher strength. The strength to weight ratio is thus much better for the composite materials compared to the more conventional materials. The conventional materials are however much more rigid with regard to shear loads than the composite materials are.

3.4 Attaching, Joining and Repairing

In the following sections assembly and repairing of composite materials will be presented. These are important aspects when it comes to application of composite materials where several different components, both composites and non-composites, are to be used together in a structure.

3.4.1 Attaching and Joining

Composite materials rarely make up the finished structure alone where they are applied. Thus it is necessary to be able to attach or join composite materials either with other composite materials or with other structural parts like metal, concrete or wood to name a few.

Three different forms of attaching or joining composite materials to other structural components will be presented in the following sections. These are riveting/bolting, bonding and inserting.

3.4.1.1 Riveting and Bolting

The introduction of holes whether molded or drilled is an introduction of weakness in the composite material. This is due to stress concentration at the perimeter of the hole. The decrease in fracture resistance can be quite much, [11] states that the reduction in fracture resistance is 40 % to 60 % for tension and 15 % for compression. However the loss of fracture resistance can be lessened by also using bonding at the time of bolting or riveting. A consequence of bonding will often be that the structure cannot be disassembled.

Different types of bolt joint failures are; tensile fracture, shear fracture, bearing failure, tensile and normal fracture, bolt fracture and bolt lifting. These types of bolt failures are more closely described in table 3.5.

Both when bolting and riveting it is necessary to ensure that the contact pressure will not damage the composite material. Often metallic washers are used to distribute the load as with application of many other materials [11, 13].

Table 3.5: Types of bolt joint failures [11].

Failure mode	Cause
Tensile fracture	Tensile fracture arises due to a lack of fibres in the primary load direction
Shear failure	Shear fracture arises as a result of to few fibres in the -45 ° and 45 ° directions
Bearing failure	Bearing failure is due to insufficient thickness of the composite material
Tensile and normal fracture	Tensile and normal failure is due to insufficient strength in both the direct and normal direction in relation to the primary load direction
Bolt fracture	Bolt fracture arises due to insufficient bolt strength
Bolt lifting	Bolt lifting is like bolt fracture due to insufficient bolt strength but is without a bolt fracture taking place

Recommendation for fibre orientations, safety factors, edge distances, composite material thickness and lengths when using bolting and riveting can be found in [11], but will not be presented here.

3.4.1.2 Bonding

Bonding of materials is done by applying an adhesive that transfers the loads between the bonded structural parts. Some of the advantages of bonding is a good distribution of stress (force per area), light weight assembly and possible insulation and sealing properties of the adhesive. A disadvantage in some applications however is that the bonded parts rarely can be disassembled. Examples of adhesives are epoxies and polyesters.

The adhesive should be loaded by shear forces. Tensional loads must be avoided because the tension strength of the adhesive is low. Different modes of failure are listed in table 3.6.

As the adhesive should be loaded in shear, the geometry of the bond is very important. Furthermore the bonded area should have an appropriate size in relation to the expected forces working on the assembled part. Guidelines for bonding geometries is given in [11]. It should however be noted here that bonding should take the form of being doubles sided to ensure the best transfer of forces between the bonded parts [11, 13].

Table 3.6: Types of failures for bonded structures [11].

Failure mode	Cause
Fracture at interface	Fracture at interface can be caused by poor bonding of the adhesive on the surface or that the adhesive is applied to too small an area compare to the forces in action or tensional loading of the adhesive
Fracture at adhesive	Fracture in the adhesive can arise due to tensional loading of the adhesive
Fracture in structural parts	Fracture in the structural parts can be caused by higher loadings than expected or poor design of the structural composite material

3.4.2 Repairing

Composite materials are generally repairable. However to what extent and how they should be repaired is very dependent on a case-by-case basis. A prime factor in this is also the application of the composite materials and the demands for safety [14].

Where composite materials are encased in other materials, like a protective housing, repairs can be impossible to perform. In other applications the damages part can be cut and replaced by undamaged material. The reinforcement of the damaged section by on-site application of further composite materials is also a possibility. Several options for repairs do exist but is very dependent on the specific materials and the application.

Thus repairs restoring the mechanical integrity should be simpler to perform compared to restoring the electrical strength of a component since this is much more sensitive to impurities than the mechanical strength.

Chapter 4

Application of Composite Materials in Overhead Transmission Line Components

An overhead transmission line systems independent on voltage level consists of three major components; towers to carry the overhead line conductors, insulators that ensure the electrical insulation of the conductor and overhead line conductors to carry the energy transported by the overhead line system. In figure 4.1 the different components are marked.

These components have traditionally not been based on composite materials at EHV levels. In the following composite materials based overhead transmission line components will be presented and evaluated.

Composite or composite material based overhead line systems is in the present thesis considered as being overhead line systems in which composite materials have been used to manufacture the major components of the overhead line system. The major components are; insulators, conductors and towers.

One of the first components to be manufactured from composite materials is insulators which were developed for overhead transmission lines in the late 1960s. The first commercial composite insulators became available during the 1970s in both Europe and the USA [25]. Composite insulators are however not the only component in overhead transmission line systems based on composite materials. Also towers and conductors based on composite materials have been developed and are in service today.

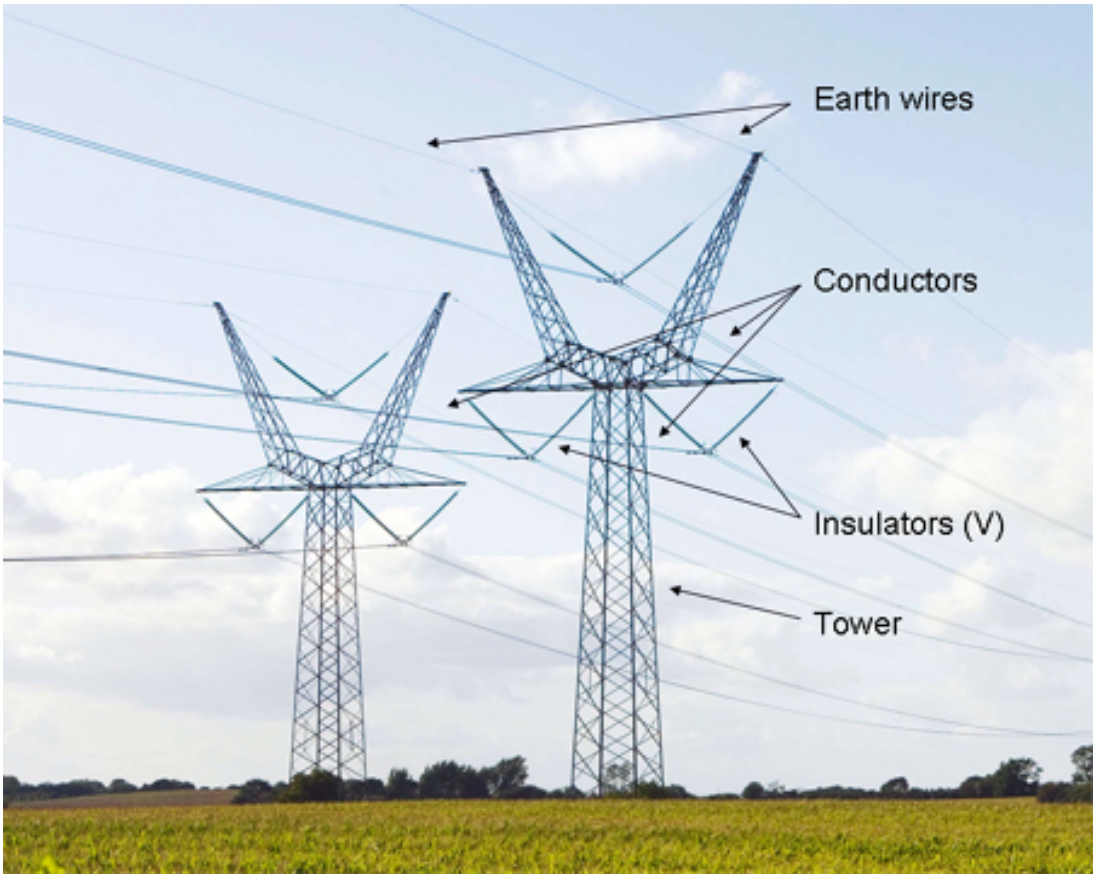


Figure 4.1: Overhead line system with marking of the major components.

4.1 Commercially Available Products

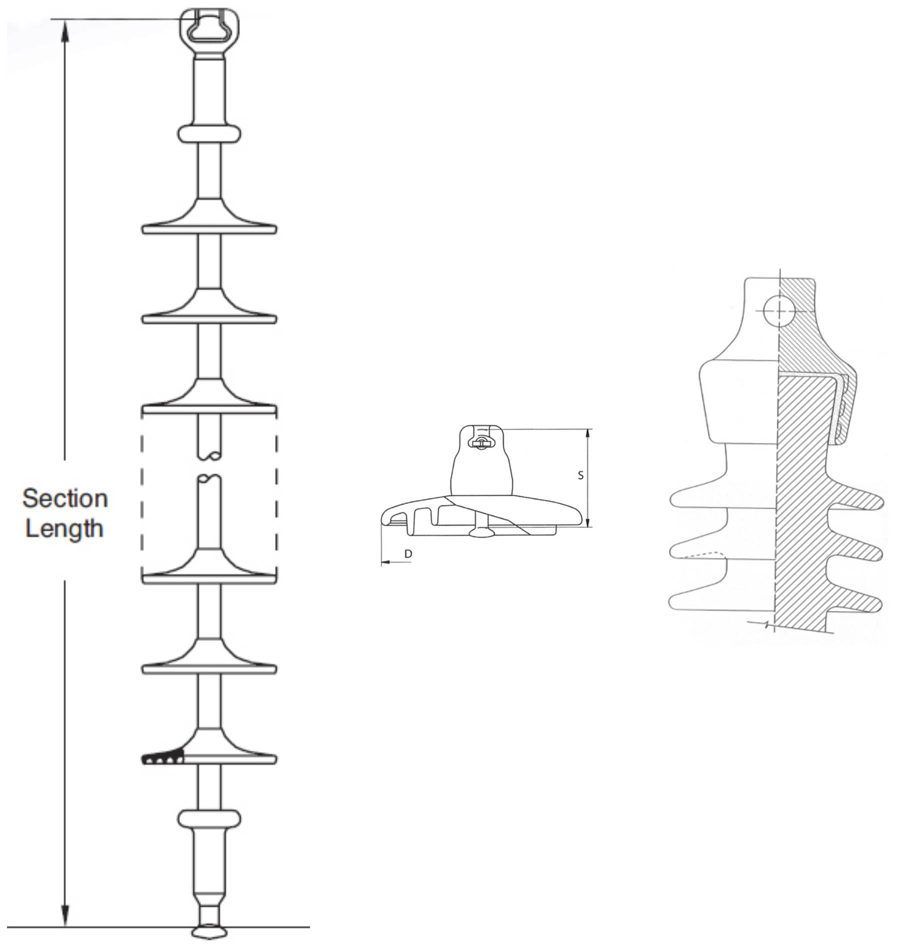
Composite based solutions for all the major parts of overhead transmission line are available today at almost all transmission levels although still somewhat limited at high voltages. In this section the different components are introduced and operation experiences are presented.

Operation experience with the different components has shown common issues but also issues more specific to the different components and their designs. Some of these operation experiences result in new challenges when using composite materials in overhead transmission line however these are often outweighed by the benefits that composite materials introduces.

4.1.1 Insulators

Insulators are an essential part of overhead line systems. It is the insulators that ensure the electrical isolation of the overhead line conductor from the tower while at the same time making it possible to connect the conductor to the tower.

The installation of composite insulators in overhead transmission line has been more widespread in the USA, China and South Africa than in Europe [26]. Nowadays, European utilities are however also using composite insulators in overhead transmission line in increasing numbers.



(a) (b) (c)

Figure 4.2: Suspension insulators based on different materials, (a) composite longrod insulator, (b) glass cap-and-pin insulator, (c) porcelain longrod insulator.

In figure 4.2 present designs of composite, glass and porcelain insulators are included. The composite insulator is limited to longrod insulator designs, glass to cap-and-pin insulators, while porcelain insulators can take shape as both longrod and cap-and-pin insulators.

The first insulators made for overhead lines were made from porcelain mounted on a metal arm. Since then insulators have evolved a great deal and porcelain insulators were generally replaced by glass insulators for overhead line purposes. Glass insulators are a product made of several different materials which are; glass, steel and fillers. However it was not until the introduction of composite insulators – insulators based on a fibreglass rod – that insulators became truly composite material based. The first composite material based insulator became available during the 1970s in both Europe and the USA after several years of development [25].

The main driving forces for using composite insulators are often stated as being good pollution performance, easy to handle and transport and less attractive for vandalism [26].

Today standard composite line insulators are available for voltage levels as high as 765 kV AC and in China several projects for DC at 800-1000 kV are using composite based insulators as these offer greater advantages than glass- or porcelain-based line insulators.

Beside line insulators other types of insulators are also being manufactured in composite materials. Examples of this are insulating crossarms. Usually crossarm insulators are a combination of post and suspension line insulators. Insulating crossarms have been developed as a mean to compacting overhead line towers [27]. Besides line insulators also post and hollow core insulators are available based on a fibreglass core.

4.1.1.1 Design

Composite insulators are applied in overhead line systems in many different designs. The one with the most experience and the one that will be given most attention here are line insulators. However besides line insulators also hollow core or post insulators are often applied in overhead line or as apparatus insulation and housing. Last but not least are insulating crossarms. These often consists of insulators from the two previous groups, however when these are combined, they are often referred to as insulator sets or insulating crossarms. These different designs will be presented below.

Line Insulators

Composite line insulators in general terms consist of a fibreglass rod covered by a rubber sheath and aluminium or steel end fittings at the core ends for connection purposes.

The fibreglass rod insures the mechanical strength of the insulator as well as the direct insulation between live and grounded objects. The rod is a pultruded unidirectional glass/epoxy rod with the fibres orientated along the length of the insulator.

The rubber housing, being silicone rubber or EPDM (ethylene propylene diene monomer) predominantly, protects the fibreglass rod from the surrounding environment as well as insuring sufficient leakage distance and pollution flashover performance of the insulator. Sufficient leakage distance is achieved by forming part of the housing as discs. The housing can either be one-cast (both sheath and discs) or a one-cast sheath with rubber discs being pulled on the rubber and afterwards vulcanisation to bond the discs to the sheath.

Several different designs of composite insulators and material compositions are being used. The final composition of an insulator is very dependent upon the manufacturer and can affect the performance of the insulator to a great extent [25, 28].

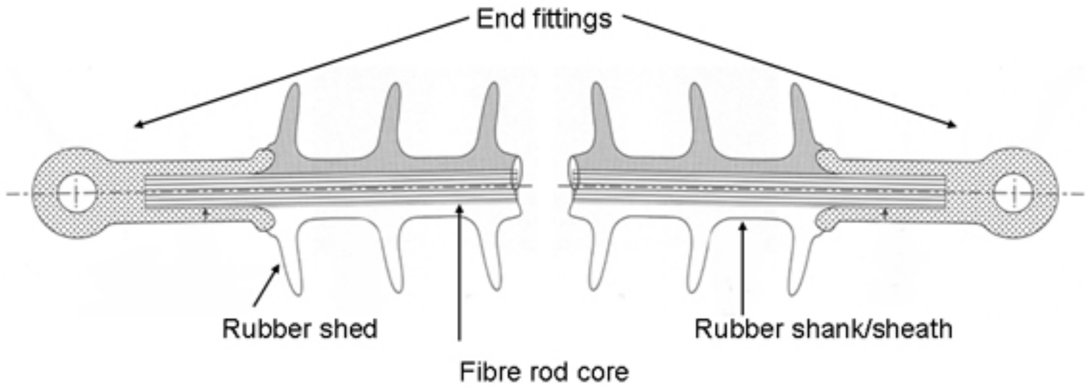


Figure 4.3: Composite line suspension insulator.

Usually composite line insulator has a slim profile with a shed diameter between 150 mm and 200 mm at EHV levels. The diameter of the rod is typically below 100 mm. These low diameters can be used since line insulators primary mechanical load is tensile load in the core's direction and load radial to the core is very limited.

Glass insulators are still the most used insulator type when it comes to line insulators in the form of cap and pin insulators. However composite insulators are slowly covering larger parts of marked and for severely polluted areas they are often the preferable choice it would seem. In China alone over 600.000 composite insulators are in service with good performances reported [29].

Hollow core and line post insulators

Hollow core and line post insulators are used in application where the forced on the insulator are not only in parallel to the insulator but also along the radii of the insulator. Hollow core and line post insulators are designed to handled greater transversal forces than line suspension insulators by an increased diameter of the core, either as a solid core or a hollow core. Furthermore variation in the fibre direction can helped these insulator types with increased elasticity modulus in the transversal direction.

Line post insulators are solid whereas hollow core insulators are hollow and thus shaped like a cylinder. Hollow core insulators are typically used as apparatus housing. Hollow core insulators can however also be filled with structural foam, adding to the rigidity and strength of the hollow core insulator. According to [29] hollow core insulators could in 2004 be made in lengths up to 6 m with an external diameter of 600 mm applied at voltage levels up to 800 kV. Hollow core insulators are produced by use of filament winding. The cylindrical core is made from E-glass fibres and epoxy resin. The core is fitted with flanges (aluminium alloy) and is afterwards coated with a rubber housing. At MacLean Power Systems the silicone rubber housing is formed as a continuous spiral whereas common housing design is sheds like on line insulators [29, 30].

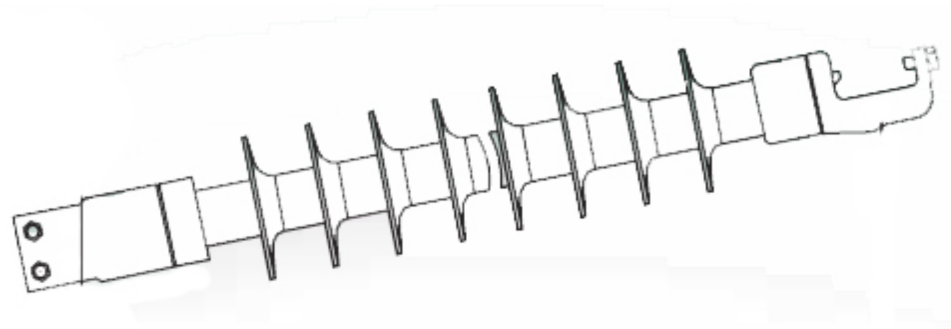


Figure 4.4: Line post insulator mounted at angled.

Insulating crossarms

Insulating crossarms are crossarms made of a nonconductive material that is applied in overhead line towers. At distribution level these can be bars made in composite materials where on the insulators are mounted. Insulating crossarms at transmission level can often be seen as a combination of different insulator types like suspension and post insulators forming a horizontal V.

Three general configurations of post and suspension insulators are used at transmission levels; braced line post, horizontal V and pivoting horizontal V. The braced line post is a line post mounted in at a fix angled in relation to horizontal supported by a suspension insulator. The horizontal V insulator set consists of a line post insulator mounted horizontally supported by line suspension insulator. The last of the three general combinations, is a pivoting horizontal V, which consist of a line post insulator mounted horizontally in with a swivel, thereby allowing the line post insulator to move in the horizontal plane. The line post insulator is supported by a line insulator, still allowing some movement of the line post insulator [31].

Examples of an insulating crossarm can be seen in figure 2.3 and 2.1. In the first case the post insulator functions both as the insulation of the line conductor and also as the mechanical crossarm being affected by forces in several directions and in the second case the post insulator is aided by the addition of suspension insulator forming a horizontal V insulator or braced post insulator which holds the overhead line.

Housing

The composite materials used in insulators typically exhibits poor surface performance under electrical applications, especially under polluted conditions. Therefore the composite materials are enclosed in housing material, typically being either silicone or EPDM rubber. Silicone has typically been favoured in Europe whereas EPDM has been mostly used in the USA. Both materials allow great flexibility in the shaping of the housing.

One of the big differences between silicone and EPDM rubber is that silicone is very hydrophobic (water repellent) which results in good electrical performance of the silicone surface under wet and polluted conditions. The housing materials are discussed more closely in section 5.1.2.2.

The rubber housing is often applied by injection moulding which is vulcanised either at room (RTV) or elevated temperature (HTV) [26, 32].

4.1.1.2 Manufacturers

Several manufacturers of composite insulators are on the market today, for all types of insulators. Some of the manufacturers are Seves Sediver, Lapp Insulators, Hubbell Power Systems, MacLean Power Systems and TCi in China. Several Chinese produce have emerged on the market over the last decade. Large component manufacturers like ABB Switchgear also make extensive usage of composite hollow core insulators for their equipment.

4.1.1.3 Properties of Selected Insulator Dielectric and Insulators

In the tables 4.1 and 4.2 some electrical, mechanical and thermal properties are presented for glass, porcelain and composite dielectrics as well as properties for commercially available insulators primarily of the line suspension type but also for a line post insulator.

Table 4.1: Properties of insulator dielectrics [33].

		Porcelain	Glass	Polymer	RBGF
Density	(kg/m^3)	2300-2900	2500	900-2500	2100-2200
Tensile strength	(MPa)	30-100	100-120	20-35	1300-1600
Compressive strength	(MPa)	240-820	210-300	80-170	700-750
Elasticity modulus	(GPa)	500-100	7.2	0.6-16	43-60
Thermal conductivity	(W/mK)	1-4	1	0.17-0.9	0.2-1.2
Thermal exp. coefficient	(10^{-5} °C)	0.35-0.91	0.8-0.95	1.5-20	0.75-2
Permittivity	(air = 1)	5.0-7.5	7.3	2.3-5.5	2.5-6.5
Loss tangent	(10^{-3})	20-40	15-50	0.1-5.0	5.0-20
Puncture strength	(kV/mm)	10-20	>25	>25	3.0-20
Volume resistivity	($\Omega \cdot$ cm)	10^{11}-10^{13}	10^{12}	10^{15}-10^{17}	10^{11}-10^{14}

One key factor that may stand out in table 4.1 are the relatively low puncture strength values for both porcelain and the resin-bonded glass fibre (RBGF) composite rod compared to the glass and polymer. It is however stressed in [33] that long term values of electrical stress above a few kV/mm are not seen in-service and that suspension insulators are one the application with the highest in-service electrical stresses.

Besides the electrical strengths, also the mechanical strengths are interesting to examine closer. Both in tensile strength and in compressive strength the composite characteristics would seem superior to the other dielectric materials. The reason why the composite material has much higher values in tensile and compressive strength is that the material is elastic until breaking. Thus the composite material will deform under loading whereby the forces are redistributed better internally in the material. Both the glass and porcelain will simply crack under high loads leading to lower mechanical strength. For glass cracking will lead to complete shattering of the glass body [24, 33].

In table 4.2 the upper range of the two manufacturers' composite line suspension and post insulators is shown. The line suspension insulators are available as standard components up to 300 kN and can be applied at up to 765 kV. For the line post insulators voltage levels up to 500 kV are included in the standard range however the cantilever loads are limited to 6-7 kN. The specified cantilever load decreases with the length of the insulator as the bending moment on the insulator increases with the insulator length.

4.1.2 Conductors

In the following sections an introduction to the different types of commercially available conductors utilising composite materials will be given and the conductors will be compared not only to one another but also to conventional conductors. The name composite based conductors will also be used for conductors utilising composite materials throughout this thesis.

The term composite conductors normally cover all conductors using different materials for core and the conducting layer of a conductor. Here however the term will refer to conductors consisting of an aluminium conductor with a core of composite materials.

The use of composite materials for overhead line conductors have matured within the last 10 years and have recently become available on a commercial basis.

Two types of composite conductors are available on the commercial market today. These are the ACCR (aluminium conductor composite reinforced) and ACCC (aluminium conductor composite core) conductors. Both the conductors offer good properties compared to ACSR conductors but are still very different conductors. Low thermal expansion and higher E-modulus gives composite based conductor the advantage of low sag. Furthermore these conductors are able to tolerate high temperatures around 200 °C under normal operation. The two composite conductors belong to the conductor group referred to as HTLS (high temperature low sag) conductors, which have low sag and can be used at high operating temperature ($>$ 150 °C). These are the most predominant advantages of

Table 4.2: Properties of commercial silicone glass/epoxy composite line suspension insulators, toughened glass line suspension insulators and silicone glass/epoxy line post insulators [31, 34, 35].

Type	Mechanical load (kN)	Voltage level (kV)	Spacing (mm)	Number of sheds	Shed diameter (mm)	Arcing distance (mm)	Creepage distance (mm)	Dry power frequency (kV)	Wet power frequency (kV)	Lightning impulse (kV)	Weight (kg)
Composite	120/160	400/500	3034/3069	101	160-190‡	2634	7561*	800	655	1435	10-20‡
Composite	120/160	400/500	3474/3509	117	160-190‡	3074	8764*	925	720	1660	10-20‡
Glass	120		127	1	255		320	70	40	100	4
Glass	120	400/500	2667	21†	255		6720	826	635	1425	84
Glass	120	400/500	3048	24†	255		7680	926	713	1610	96
Composite	210/300	400/765	3530/3571	115	160-190‡	3047	8773*	915	715	1650	15-25‡
Composite	210/300	400/765	4025/4066	133	160-190‡	3542	10035*	1060	785	1900	15-25‡
Glass	210		170	1	280		380	75	45	110	7.2
Glass	210	400/765	3400	20†	280		7600	970	710	1690	144
Glass	210	400/765	3910	23†	280		8740	1090	805	1920	165,6
Line post insulator											
Composite	7.7§	400/500			(63.5)^{D}	2233	5766	880$^{\sharp}$	540$^{\sharp}$	1220	
Composite	6.1§	400/500			(63.5)^{D}	2847	7366	1105$^{\sharp}$	655$^{\sharp}$	1570	

* Larger creepage distances can be achieved with other sheds designs available from the manufacturer. Larger creepage distance does not affect the withstand voltages.
‡ Exact diameter and weight are unknown. Estimates are based on [36, 37] listed instead.
† For the glass insulators the number of sheds have been chosen based on respectively the lightning withstand voltage and creepage distance of the first composite insulator in each group.
§ Specified cantilever load. Tensile load 33.4 kN.
^{D} Only rod diameter supplied.
$^{\sharp}$ Power frequency voltages are 60 Hz values. The dry power frequency withstand voltage is based on ANSI standards.

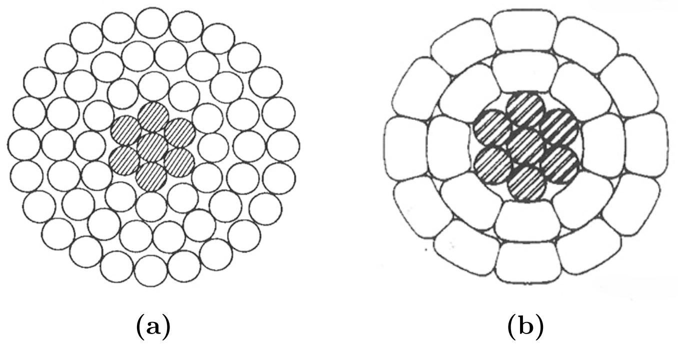


Figure 4.5: Cross section of a bi-material overhead line conductor, (a) with round wires and (b) with trapezoidal wires. Courtesy of Southwire, from [38]

the ACCC and ACCR conductors. The conductors will be presented with greater detail in the following [39, 40, 41].

Conductors are the current carrying part of overhead line systems. They are the motorway for electricity so to say. Conductors used for EHV AC transmission have conventionally been aluminium conductors (AAC – all aluminium conductor – or AAAC – all aluminium alloy conductor) or of steel reinforced aluminium (ACSR). In Denmark only ACSR conductors are used at transmission level.

Overhead line conductors have conventionally been made out of copper, aluminium or aluminium with steel reinforcement. Copper have mostly been used on distribution level and is today generally only used for cables. Aluminium conductors are today used on both distribution and transmission level in some countries. However for transmission levels aluminium conductors with steel reinforcement (ACSR) are used as the conventional type of conductor though this is dependent on company preferences and demands loading situation. Depending on the strength requirement of the line, the steel to aluminium ratio can be varied.

Other variants of conductors based on steel and aluminium are also commercially available. These are generally based on heat resistant aluminium and use of other internal conductor geometries i.e. gap conductor where a gap is introduced between the conductor and the core, which carries the entire mechanical load. Other conductor such as the ACSS (aluminium conductor steel supported) conductor exploit the better sag parameters of the steel core by making sure that the aluminium is slack on the steel core upon installation whereby the core carries the mechanical load. These conductors have been available for many years [42].

The ACCC and ACCR are the only composite material based conductors commercially available. The ACCC conductor was introduced in 2003 and the ACCR conductor in 2001. Both conductor types are today installed at numerous sites around the world. Other composite material based conductors are reported as being under development. However information on these have not been readily available and are therefore not included here.

4.1.2.1 Design and Characteristics

In the following sections, the design and properties of the composite conductors will be presented.

Design – ACCC

The ACCC type conductor consists of an aluminium conductor supported by a glass fibre epoxy covered carbon fibre epoxy composite core. Figure 4.6 shows an angled cross section of the ACCC conductor.

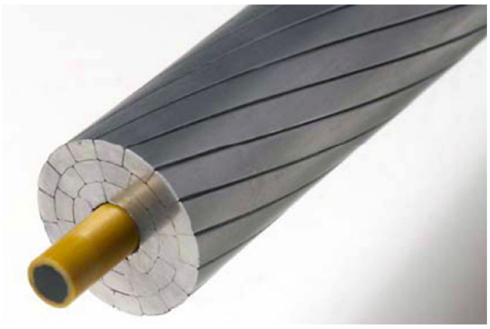


Figure 4.6: The aluminum conductor composite core (ACCC) type conductor [43].

At the moment around 10,000 km of the conductor is installed. The price of the conductors is reported to be around 2-3 times the price of an ACSR conductor [44, 45].

Core

The core of the ACCC conductor is divided into two layers which can been seen from figure 4.6. The innermost layer is made from high modulus carbon fibres embedded in epoxy. The innermost layer is surrounded by a protective layer of glass fibre embedded in epoxy. The glass fibre layer insures that no chemical reaction between the aluminium conductor and the carbon core can take place and thus ensures the mechanical integrity of the conductor core with time [43].

Conductor

On the core is spun one or more aluminium layers which make up the conducting part of the conductor. The aluminium strands are trapezoidal in shape and thus the fill factor - ratio of utilised cross section - is high. At the moment annealed aluminium (thermal resistant aluminium - TAL) is used for the ACCC conductor. Because annealed aluminium is used, the core must carry the entire mechanical load on the conductor, as the strength of the annealed is drastically reduced compared to un-annealed aluminium. This however also results in that the sag of the conductor will be small due to the core's stiffness.

As annealed aluminium is used, the operating temperature of the conductor can go beyond the temperatures at which aluminium usually starts to anneal at. The annealed aluminium be operated continuously at temperatures up to 200-250 °C. However due to the core composition the actual continuous operating temperature is recommended not to go beyond 180 °C as the mechanical strength of the core else will be slowly reduced [43, 46].

Installation

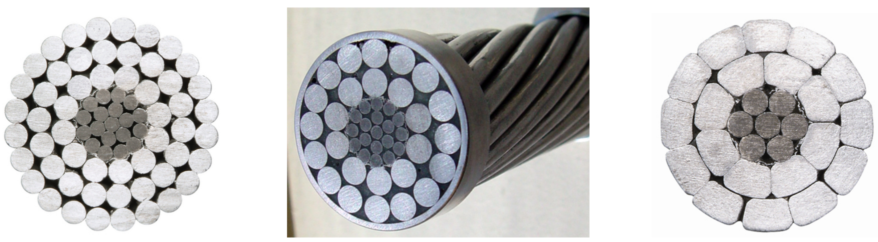
The conductor is installed in such a way that the core carries the entire mechanical load on the conductor. Due to the special design of the core of the conductor, the ACCC conductor cannot be installed fully conventionally. Special grips for dead-ends are required to ensure that the core is not subjected to excessive compressive forces.

During the installation of the conductor, minimum bending radii must not be overstepped to ensure that the core is not subjected to bending forces that can lead to breakage of the core and thus reduced mechanical strength of the conductor. This is however avoided by use of the right reels [43, 46].

Design – ACCR

The ACCR conductor makes use of a core based on aluminium oxide fibres in an aluminium matrix. The conductor was introduced in 2001. Only around some thousand kilometres of the conductor type are installed at present. This relative low number of installed line km should be viewed together with the price of the conductor which is around 10 times the price of ACSR conductors [45].

Pictures of the cross section of the ACCR conductor is included in fig 4.7.



(a) (b) (c)

Figure 4.7: The aluminium conductor composite reinforced (ACCR) type conductor, (a) ACCR cross section, (b) ACCR, (c) ACCR-TW [47]. Courtesy of 3M.

Core

The core of the ACCR conductor is made from strands of aluminium oxide fibres imbedded in an aluminium matrix – a fibre reinforced metal matrix. This composition ensures a high strength, low weight core. The core of the conductor is constructed in the same manor as a ACSR conductor, as the composite strands of aluminium oxide fibres in aluminium are twisted around one another to form the core of the conductor.

Conductor

The conductive outer layers are made from aluminium-zirconium strands. The addition of zirconium to the aluminium ensures a higher operating temperature (up to 250 °C) of the aluminium without annealing the aluminium. Thus the aluminium layer retains its tensile strength even under high operating temperatures and can contribute to the strength of the conductor.

The outer aluminium layers can both be made as trapezoidal and round strands and the ACCR conductor is commercially available with both wire types. The two types of wires can be seen in figure 4.7. The ACCR conductor with trapezoidal shaped aluminium wires is named ACCR-TW [40].

Installation

The ACCR conductor can installed in a similar manner as ACSR conductors. The conductor dead-ends can be equipped with compressive fittings however compared to ACSR a higher pressure is needed. Furthermore it is recommended that the line is installed with armour-rod grips at suspension insulators [48].

4.1.2.2 Conductor characteristics for selected ACSR, ACCC and ACCR conductors

Properties for a selection of the ACCC and ACCR conductors are included together with data for ACSR conductors in tables 4.3 and 4.4.

Several different cross sections for the conductor types are available from the manufactures. Here, however, the number of conductors has been limited to conductors of approximately the same diameters as the conductors used in the Danish transmission system; ACSR Condor and ACSR Martin.

As stated above the ACCC and ACCR conductors in tables 4.3 and 4.4 have been chosen based on that fact they have approximately the same diameter as the ACSR Condor and ACSR Martin. The diameter is chosen as the reference parameter since this will be

Table 4.3: Conductor characteristics for selected ACSR, ACCC and ACCR conductors [39, 40, 42].

		Cross section (mm^2)			Diameter (mm)		Weight (kg/m)			Strength kN	E-modulus (N/mm^2)	
Type	Name	Total	Aluminum	Core	Total	Core	Total	Aluminium	Core		Below T_{knee}	Above T_{knee}
ACCC	Warsaw	574.9	514.6	60.3	27.72	8.76	1.5388	1.4258	0.113	159.1	63,000	118,300
ACCC	London	841.1	766	75.1	33.4	9.78	2.2663	2.1246	0.142	205.2	62,000	118,600
ACCC	Antwerp	1027	951.9	75.1	36.85	9.78	2.7778	2.6359	0.142	215.7	61,000	118,600
ACCR	Drake	484	418	66	28.6	10.6	1.384	1.155	0.229	143.3	83,500	230,000
ACCR	Pheasant	723	642	81	35.0	11.7	2.063	1.784	0.291	191.3	78,600	250,000
ACCR	Martin	761	676	85	35.9	12.0	2.172	1.878	0.294	201.5	78,600	250,000
ACCR-TW	Suwanee	562	486	76	28.1	11.3	1.600	1.338	0.262	164.9	83,500	230,000
ACCR-TW	Rio Grande	876	777	99	35.1	12.9	2.494	2.153	0.342	233.6	78,600	250,000
ACCR-TW	Pecos	927	822	105	36	13.3	2.639	2.278	0.361	247.4	78,600	250,000
ACSR	Condor	454	402	52	27.7		1.522	1.087	0.405	127.0	60,000	180,000
ACSR	Martin	772	685	87	36.2	12.0	2.574	1.895	0.679	211.7	57,000	175,000

Table 4.4: Conductor electrical and thermal properties for Selected ACSR, ACCC and ACCR Conductors (continued) [39, 40, 42].

Type	Name	DC resistance (Ω/km) Total	($^\circ$C) at temp.	Max. cont. temp. ($^\circ$C)	Thermal exp. coefficient (10^{-6} K^{-1}) Total	Core	Heat capacity (W · s/m · $^\circ$C) Aluminium	Core
ACCC	Warsaw	0.0545	20	180 (200)	18.8	1.61	1251	
ACCC	London	0.0366	20	180 (200)	18.8	1.61	1843	
ACCC	Antwerp	0.0295	20	180 (200)	18.8	1.61	2258	
ACCR	Drake	0.0658	20	210 (240)	17.1	6.3	1102	75
ACCR	Pheasant	0.0437	20	210 (240)	17.1	6.3	1700	92
ACCR	Martin	0.0415	20	210 (240)	17.1	6.3	1790	97
ACCR-TW	Suwanee	0.565	20	210 (240)	17.1	6.3	1,277	85
ACCR-TW	Rio Grande	0.0360	20	210 (240)	17.1	6.3	2,053	112
ACCR-TW	Pecos	0.0340	20	210 (240)	17.1	6.3	2,172	119
ACSR	Condor	0.07183	20	80 (90)	19.3	11.5	975	195
ACSR	Martin	0.04227	20	80 (90)	16.4	11.5	1700	327

important for ice loads and wind loads on the conductors and thus for the tower structures of the system.

The noticeable differences for ACCC and ACCR conductors compared to ACSR conductors are that for the TW strands a much higher amount of aluminium is present for the same conductor diameter. This also results in lower resistances for the TW conductors, but at the same time increases the weights of the TW conductors compared to the ACSR conductors, which will affect the sag of the conductors.

For the ACCR conductor with round aluminium wires, the weight of the conductor is about the same as an ACSR conductor of similar diameter. The tensile strength of the ACCR and ACCC conductors are comparable to ACSR conductors. The elasticity modulus or stiffness of the two conductor types are however much higher than for the ACSR conductor even though the ACCC's elasticity modulus might look lower than the ACSR conductor's. This is due to that the ACSR conductor will typically be operated below its kneepoint temperature whereas the ACCC conductor will operate above (the kneepoint temperature of the ACCC conductor corresponds to the installation temperature). The thermal expansion coefficients of the composite based conductors are lower than the ACSR conductors', resulting in lower elongation under heating of the ACCC and ACCR conductors compared to the ACSR conductor.

Due to the higher content of aluminium in the TW conductors, the heat capacity of the conductors will be greater than for the round wire conductors. The heat capacity of the conductor is important under loading changes on an overhead line conductor. This is discussed further in section 6.2.3.

The final important parameter is the operating temperature of the conductors. The operating temperature will set the upper limit for the thermal loading of the conductors and thereby the maximum current that the conductors can carry without degradation of the mechanical properties. Here the composite conductors can be operated at temperatures well above the ACSR conductors.

In Cigré Brochure 244 [49] several other types of conductors are presented. Some of these may offer the same or better characteristics than ACCC and ACCR conductors dependent on the specific case for application of the conductors.

Comparison of ACCR and ACCC with ACSR conductors

In table 4.5 the strength and weaknesses of the ACCC and ACCR conductors compared to ACSR conductors are listed to give an overview of the differences.

Table 4.5: Strengths and weaknesses of ACCC and ACCR conductors compared to ACSR conductors [43, 48].

	ACCC	ACCR
Strengths	High strength vs. weight ratio Higher conductivity due to larger amount of aluminium per radii Low sag and thermal expansion Maximum continues operating temperature 180 °C No creepage of core Conventional installation tools are usable More corrosion resistant	Looks like a conventional ACSR conductor High strength vs. weight ratio Larger amount of aluminium per radii (for TW type) Low thermal expansion coefficient Maximum continuous operating temperature 210 °C Conventional installations tools are usable More corrosion resistant No creep of core High elasticity modulus
Weaknesses	Demands to minimal bending radius during installation Special fittings to ensure load distribution to core Annealed aluminium must be handled with care Instable core at very high temperatures (> 200 °C)	Possibility of micro cracking of the ceramic fibres Special clamps to avoid radial pressure in the core

4.1.2.3 Manufacturers

There is one commercial version of the ACCC conductor on the market today. The conductor is developed by CTC Cable Corporation [39] and is protected by international patent WO 03/091008 A1 [50]. A second version of the ACCC conductor is possibly being developed by Nexans [51]. However information on the Nexans conductor has not been accessible to a satisfactory extent to be included here.

ACCR conductors have been developed by 3M [47] and are describe in international patent WO 02/06550 A1 [52].

Both conductors are typically manufacturer and processes at different locations. The cores are manufactured at either CTC or 3M and shipped to conductor suppliers, whom manufacturer the final ACCC or ACCR conductors by stranding aluminium on the core [43, 48].

4.1.3 Towers

Towers are the carrying part of the overhead line system that ensure that the conductors are kept at safe distance from one another and to the general public. Towers are typically made of steel and sometimes in part of concrete. At lower transmission levels also wood are used as pole towers.

In 1960's fibreglass poles were installed in Hawaii. These where in service for 45 years before they were exchanged with new fibreglass towers. Many advances have been made since the first fibreglass towers and today fibreglass towers can also be utilised for transmission levels [53].

In the USA composite based towers for distribution levels have been used in many years. The towers are now also available for lower–middle transmission level as a standard component.

Another approach to composite based towers is concrete towers reinforced with rods based on composite materials. These are based on conventional building techniques with steel reinforcement replaced by carbon fibre epoxy rods. These have been applied to voltage levels up to 110 kV [27].

The main part of the commercially available composite towers is made from one piece pultruded glass fibre reinforced plastics. However several examples of other ideas can be found in the literature. In example a tower with a built in down-conductor in hollow core insulators with connecting flanges where overhead line conductors can be connected [54].

4.1.3.1 Design

Composite material based towers are primarily produced through two methods; filament winding and pultrusion. The choice of fabrication will affect the properties of the towers as the methods give rise to different strength and weaknesses [53, 55, 56].

Composite towers are typically made of glass fibres imbedded in a resin. For tower application the fibres are typically multidirectional to ensure the towers can also handled the torsion forces on the towers. Currently a maximum standard fibreglass tower height of 34-41 metres is available dependent on manufacturer. These towers have been used in overhead transmission line up to at least 115 kV, often as a replacement for wooden poles [53, 57, 58].

No matter the choice of manufacturing process the preferred materials are glass fibres for the reinforcement and a thermoset matrix. However also examples with carbon fibre epoxy rod reinforced concrete can be found in the literature [27, 55].

One design of a composite tower uses modules that are connected to form the finished tower. In this way several different heights can be made with standard components [53]. Also designs where the tower is made from two halves that are snapped together to form the tower have been seen in the available literature [59].

4.1.3.2 Manufactures

Several different manufactures exists for composite materials based towers at the lower transmission levels. The manufactures are however primarily located in North America.

All of the North America manufacturers included here makes used of fibreglass for the production of the composite towers. The European manufacture on the other hand makes use of carbon fibre rods as reinforcement for spun concrete towers. An overview of some manufactures is listed in table 4.6.

4.1.3.3 Summery

In table 4.6 an overview of different composite based towers is given. All of the manufacturers make use of fibreglass materials for the production of their towers with the exception of the one manufacturer which make use of concrete reinforced with carbon-fibre/epoxy rods.

The current limitation for the different composite poles as standard elements are given in table 4.6. The height of the towers is one of the most important factors as this determines which sags can be allowed on overhead line conductors, as the electrical clearances to the general public must be kept. At present the heights that the towers are available in are limited to 41 m. Some experience with application of composite towers is reported in literature. According to this, the maximum voltage levels at which the examined towers have been applied are 115 kV. The voltage levels is again dependent on the height, as higher voltage levels leads to higher demands for clearances and therefore also increased tower heights. As the height of the tower increases, the towers also need to be able to handle a bigger bending moment.

The manufacturers estimates on life expectancies and the need for maintenance are also listed in table 4.6. There are some differences between the towers but this can most likely be related to the different materials used by the manufacturers. Generally the life expectancies are over 50 years and in some cases up to 80 years. This is with little to no maintenance, which is only specified as necessary in a few cases. Maintenance, where necessary, consists of reapplication of painting to ensure the towers UV-resistance. The reapplication of painting is only necessary once in the towers life time.

The use of composite towers are further examined in section 5.3.

Table 4.6: Comparison of composite towers [27, 53, 56, 57, 58, 59, 60, 61].

Manufacturer	Composition	Max. height (m)	Life expectancy (Years)	Used at voltage level (kV)	Maintenance requirements
RS Technologies	Glass fibre reinforced polyurethane	41 (modular)	65 (warranty 41)	–	–
PowerTrusion	Pultruded glass fibre reinforced polyurethane	18.3	50-80	< 100	Maintenance free
SACAC	Carbon fibre reinforced plastic reinforced concrete	27	50	110	
Shakespeare	Glass fibre reinforced	38.1	–	–	"Virtually" maintenance free
Strongwell	Pultruded E-glass fibre reinforced vinylester filled with polyurethane foam	24.4	50-80	115	Very little (per 25-30 years)

Chapter 5

Composite Components Exposed to Electrical, Mechanical, Thermal and Environmental Effects in Overhead Line Systems

Components of overhead line systems are stresses by several different factors being electrical, mechanical, thermal or environmental in nature or more often combinations hereof. In this chapter, how the different stresses affects the different components and which failure mechanisms that can arise are presented and discussed. The chapter is divided into sections on each of the three main components insulators (and insulating crossarms), conductors and towers treating each component separately. Each component section is concluded with a short comparison to the corresponding conventional overhead line system component.

5.1 Insulators and Insulating Crossarms

In [62] stresses on insulators besides electrical are stated as being of secondary importance since the insulators are dimensioned for the environmental, thermal and mechanical stresses as long as the manufacture recommendations are followed. Only in connection with electrical stresses should the other types of stresses be of primary concern. This is perhaps a truth with modifications and the different stresses and resulting failure mechanism for composite insulators and insulating crossarms will be presented in the following.

An insulators two main functions are electrical and mechanical in nature; ensuring the electrical insulation of the overhead line under power frequency voltages – and also keeping flashovers due to pollution and transients to a rare occurrence – and hold the line conductor mechanically under everyday loads ensuring line dropping will not take place [29].

There are many different approaches to designing composite material based insulators and the experience is still relatively limited with the many different options. An important part of choosing which composite insulator to use is to build on others previous experiences. Therefore in the following sections the failure modes and degradation mechanisms of insulators will be presented [62].

5.1.1 Insulator and Insulating Crossarm Failure Modes

Failure of an insulator independent on the type of insulator is here defined as either electrical or mechanical failure of the insulator.

An electrical failure is defined as the insulator being unable to support the power frequency voltage across the insulator. The inability of the insulator to support the power frequency voltage will either take place through flashover of the insulator along the insulators surface or through flashunder, where the "flashover" of the insulator takes place under the rubber of the insulator. Flashover and flashunder constitute two failure modes of composite based insulators.

Besides the two electrical failure modes described above also two mechanical failure modes exists. Mechanical failures are here defined as the insulator inability to hold the mechanical everyday mechanical load on the insulator. Mechanical failure of the insulator can either take place through breakage of the core rod of the insulator or through end fitting pullout resulting in the separation of one of the end fittings from the insulator. A mechanical failure will thus lead to line conductor dropping.

Insulators and insulating crossarms have four general failure modes as presented above. These can be caused by several different failure or degradation mechanisms that can lead to failure of insulators by one of the four failure modes.

5.1.2 Electrical Failure Mechanisms

Insulators on overhead lines are placed between components at full voltage potential and zero potential and are therefore subjected to full voltage at the high voltage end and decreasing voltage from full potential to zero potential at the ground end of the insulators, (see figure 5.1). Under normal operation insulators are therefore subjected to an electrical field which is dependent on the phase-to-earth voltage, the insulator length and shape of the insulators.

Due to the electric field and pollution on the insulator surface, insulators may also be subjected to leakage currents or arcing currents leading to tracking and corrosion of the insulator. Furthermore the electric field may drive internal tracking or corrosion due to poor bonding or due to voids in the materials or at the interfaces.

Besides power frequency voltage effects flashover currents and transients voltages affecting the insulator due to lightning and switching overvoltage transients can also influence the ageing and the performance of insulators in overhead line systems. These can lead to puncture or power arc termination on insulators which can result in serious damage [33, 62].

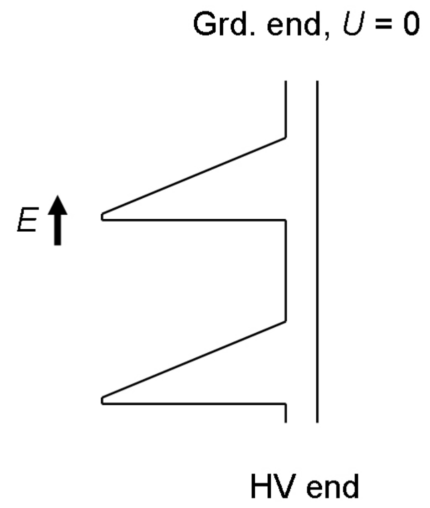


Figure 5.1: Depiction of the electrical environment in which an insulator operates.

In the following sections the effects and potential consequences for composite insulators in overhead line systems will be examined closer.

5.1.2.1 Transients

Switching and lightning events on an overhead line can lead to increased voltages across the insulators or power arcs across the insulator. This can result in either puncture of the insulator or termination of the power on the insulator housing or end fitting. The possible failure mechanisms due to this is described in the following.

Insulator Puncture

Puncture of insulators can happen when the volt-time strength of the air surrounding the insulator is larger than the insulators volt-time strength due to extreme voltage rise under an overvoltage across the insulator. The volt-time strength of insulators has little increase in voltage strength at short times compared to the insulation strength of air. Thus under extreme voltage rise across the insulator, the insulator could puncture since the voltage-time strength of air is larger than the insulator's [62].

For composite insulators puncture of sheds will leave a hole where the puncture has taken place. As long as the puncture have taken place in the sheds and not at the shank of the insulator, which could expose the core, the electrical and mechanical strength is unaffected and thus have no serious consequence for the functionality of the composite insulator. Glass insulators in contrast to composite insulators will shatter if punctured and thus at least one of the insulators units would need replacement. The electrical strength of glass insulators will be reduced if subjected to puncture. Composite insulators therefore have superior puncture strength compare to glass insulators [62].

Power Arc Termination

Power arcs may terminate on end fittings or corona rings due to lightning or switching flashover of insulators. The power arc root has a high temperature and high energy dissipation which could result in burning at the power arc root point. Power arcs terminating can lead to damage to end fitting seals which is the most likely attachment point. Damage is more probable if the end fittings are made of aluminium since aluminium has a low melting point compared to the power arc root temperature. Other damages to end fittings that can occur are loss of galvanisation on steel end fittings and damage of fibreglass rod or rubber housing.

The best way of preventing power arc damage to insulators is to use electric field grading rings (also called arcing horns) that can withstand termination of power arcs. These have been applied for many years on conventional line insulators [63, 64].

In [65] power arc termination test on a 110 kV composite silicone insulator was carried out and compared to a test on a ceramic insulator. The test showed that the composite insulator suffered blackening of the composite housing however without loosing the hydrophobicity or melting of the end fittings. The blackened layer on the insulator housing could easily be removed. No rupture or exposure of the core was detected. Electrical strength test was carried out after the power arc test and no significant deterioration of the electrical strength could be detected. The mechanical strength of the insulator was also intact. The ceramic insulator suffered damage to the ceramic housing resulting in chipping of the housing but no significant deteriorations was reported to the electrical and mechanical strength. The tests were carried out both with and without protective rings.

Thus power arc termination should not be an issue if grading rings design for power arc termination is used. Even without protective grading rings composite insulators have shown good performance in test. However termination of the power arc on the housing material or the end fitting could lead to exposure of the core and lead to other processes that could deteriorate the mechanical and electrical strength of the composite insulators.

5.1.2.2 Power Frequency

Insulators and insulating crossarms are under constant power frequency voltage when the overhead line is in operation and will thus be affected by the electrical field resulting from the voltage distribution and design of the insulator. For overhead line insulators at transmission level the electric field across the insulator will be non-uniform. The electric field will be lowest at the ground end of the insulator and highest at the high voltage end of the insulator. Thus the highest electrical field under normal operation will be on the high voltage end fitting and the housing (sheds and shank) closest to the high voltage end fitting [66].

Internal Partial Discharges

During the manufacturing of composite materials and composite components cavities or voids may arise. These can, when the component is under electrical stress, give rise to internal partial discharges (PD) and subsequent failure of the component given enough time [67].

PD will arise in cavities or voids if a critical electrical field value is reached. This can lead to several different faults; corrosion of the fibreglass core, damage to rubber housing exposing the core to the environment with long term subsequent failure or tracking along or through the fibreglass rod leading to flashunder (flashover under the insulator housing). Internal PD can also arise due to moisture or pollutants ingress in combination with the electrical field. This is best avoided by insuring the integrity of the housing material [62].

The combination of cavities or voids with the non-uniform electric field distribution on EHV line insulator can result in internal tracking near the high voltage end of the line insulator where the electric field is at its highest. The usage of corona or electric field grading rings does not mitigate this potential problem as this will not affect the electric field significantly internally in the insulator. The internal tracking, if allowed to develop, can result in electrical or mechanical failure of the insulator.

Problems with internal PD in line insulators due to voids or cavities are reported as being an issue primarily with first generation composite line insulators. As the knowledge of the cause for void and cavity formation became known, the manufacturing process was adjusted to counteract formation of voids and cavities. This is done through control of the pulling speed and temperature during the casting of fibreglass core rod and through control of injection speed and temperature in moulding of the housing to the fibreglass core [28].

Brittle Fracture

The first cases of brittle fracture or stress corrosion cracking were reported in the 1970's shortly after composite line insulators were putt into service. It caused great concern that composite insulators experience mechanical failure under low mechanical loading as there was seemingly nothing wrong before the units failed. Many advances have since been made with regard to brittle fracture and the process leading to brittle fracture has been thoroughly investigated. It should be noted that in 2002 brittle fracture was estimated to take place on under 1 out of 10.000 composite insulators in service, which includes all insulator generations and have thus most likely fallen as old generation are removed from service [68].

Brittle fracture or stress corrosion cracking is a failure mechanism that leads to complete mechanical failure of the rod due to the electrical environment. The core is attacked on two fronts when exposed to the elements (water solution) under PD. The fibres will be leaches of non-siliceous ions and the matrix is hydrolysed by the water. More precisely the glass fibres are leached of aluminium and calcium ions through contact with water leaving a silica skeleton around an uncorroded fibre core. This leaves the attacked fibres with a cracked surface which prolongs through the attacked fibres when put under load. Thus the attacked fibres can break under even light loads, leaving the rest of the fibres in the fibreglass core to carry the mechanical load on the insulator. As more fibres are attacked the load on the rest of the core is increased until the core finally fails mechanically and total separation occurs [62, 68].

Other factors that could possibly lead to brittle fracture are reported in [68]. These could be non-acid processes like hydration, hydrolysis or ion exchange. These processes can also take place on both E-glass and E-CR-glass (chemical resistant glass). Today usage of boron-free E-glass fibres called chemical resistant (CR) glass fibres are recognised as a very brittle fracture resistant solution. Some even go as far as calling boron-free E-glass immune to brittle fracture even though this is not fully the case [62, 68, 69].

A large part of brittle fractures are reported to have taken place on line insulators with breach of end fitting seal. The breach is most likely to happen due to poor bonding or bad design of end fittings to core and housing. Furthermore also breach of line insulator housing can lead to ingress of water which together with PD can lead brittle fracture of the insulator. The exposure of the core to PD along with water ingress with subsequent formation of harmful acids can take place through several mechanisms. The key is avoiding exposure of the core to the external environment [28].

In was made likely in [68] that brittle fracture is not a developing phenomenon that will slowly spread to all composite insulators but more likely a result of units there were damaged or defect before being put into service. Thus the investigations presented in [68] lead to an estimate that 2/3 of insulator failures were due to manufacturing errors and 1/3 due to costumers handling of line insulators.

The time dependency of brittle fracture is hard to predict as it is very dependent on the service environment and stresses on the insulator. Also the risk of exposure of the core is hard to asses. In [68] the time for brittle fracture to develop is stated as being days to years.

Interestingly, brittle fractures have only been reported for line insulators. In an IEEE Task Force Report [68] it is specifically noted that no line post insulators have been reported to fail due to brittle fracture these where however also a part of the IEEE Task Force investigations and may be all together free of brittle fractures. Reasons for this are reported likely to be; lower electrical stresses and thus less risk of PD, better washing (less pollution) and better evaporation leading to shorter periods where hydrolysis can take place [28, 62, 68, 70, 71, 72, 73, 74].

External Partial Discharges

Corona or PD can arise on line insulator under rain, due to high humidity or due to pollution on the surface of the insulator. When PD is present along with water the prerequisites for formation of NO_2 and O_3 is present. This can lead to oxidisation of the rubber housing leading to breakage of the carbon backbone of the rubber housing. The oxidisation could lead to exposure of the fibreglass core. The nitric or oxalic acids formed under the PD can then attack the fibreglass core and also hydrolysis with the presence of water can take place. This could in turn lead to brittle fracture (see 5.1.2.2) [28].

Mould lines on sheds and sheath can lead to concentration of corona along the mould line which in turn leads to increased corrosion and in some cases cracking of the mould line which could constitute a weakness by exposing the core. Based on service experience the thickness of the rubber sheath on composite insulators is also of importance with respect to water ingress and exposure of the core. A minimum thickness of at least 3 mm is recommended in the literature [62, 75].

End Fittings and E-grading Rings

End fitting design and use or lack of use of electric field grading rings are import in relation too external PD failure mechanisms as PD can lead to degrading of housing and end fitting seals. As seen with brittle fracture in some cases PD can be a factor in mechanical or electrical failure of composite insulators.

Flange design in relation to PD is important, as the wrong flange design can lead to water collection at the line end of suspension insulators and give rise to increased corona activity, resulting in sealant failure and water ingress in the interfaces between the end fitting and the core as a consequence [69, 76].

Grading rings on line insulators are essential at high voltage levels to avoid or lessen corona development around end fittings due to the high electric field at the insulator ends. Corona activity can result in corona cutting on the housing or end fitting but also the formation of harmful acids that can attack the housing if it can collect on its surface. Roughening of the insulator surface leads to better water collection on the surface and thus increases the risk of flashover due to pollution and water collection under power frequency or service voltage. Roughening of the housing can further lead to reduction in the corona inception voltage contributing further increasing the risk of flashover even further [28]. This also increases the aging of the housing. Furthermore radio and TV interference can be result of corona activity. For more information on Radio and TV consult [62] or [29].

Corona activity will typically be most predominant around the high voltage end of line insulators as the high electric field will be present here. As the voltage level increases corona activity around the earth end fitting can also arise as well along the shank or sheds of the insulator. At around 100 kV and above grading rings are recommended for the line end of the insulator. As the voltage level is increased grading rings at both ends of the insulator is recommended [76, 77]. IEEE have made specific recommendations for application of grading rings which are reproduced in table 5.1.

Table 5.1: IEEE recommendations for application of electric field grading rings [64].

	Suspension and dead-end insulators	Post and horizontal V insulators	Phase-phase insulators/spacers
< 161 kV$_{pp}$	-	-	May not be necessary
> 161 kV$_{pp}$	-	-	Both ends
< 230 kV$_{pp}$	May not be necessary	May not be necessary	
230-345 kV$_{pp}$	At HV end	At HV end(s) – *one ring covering both ends may be possible*	-
> 345 kV$_{pp}$	At both ends	At HV end(s) – *one ring covering both ends may be possible*	-

For suspension and dead-end insulators grading rings should not be necessary below 230 kV$_{pp}$. However above 230 kV$_{pp}$ grading rings should be used at the live end up to 345 kV$_{pp}$ and at both ends above 345 kV$_{pp}$.

For horizontal V and post insulator configuration the recommendations are that below 230 kV$_{pp}$ grading rings may not be necessary. However above 230 kV$_{pp}$ gradings rings should be used at the live end of all insulators in the configuration. Use of one grading ring covering all HV ends could be possible. For phase-phase spacers grading rings are recommended at both ends above 161 kV$_{pp}$.

For the grading rings to be effective and to ensure that the grading rings do not increase the corona problem, correct placement of the rings are essential. Several examples of incorrect instalment have been reported which can result in poorer performance than composite insulators without grading rings [69].

In the Cigré survey on experience with composite insulator from 2000 [26] it was examined which practice was used for application of grading rings. The conclusion is that practice and recent recommendation for application of grading rings does not match. Several cases of application of composite insulators without grading rings where recommended by IEEE are reported. In Europe only 7 out of 33 replying utilities in 2000 applied grading rings at the high voltage and ground of on composite insulators installed at 300 kV to 500 kV. Between 200 kV and 300 kV only 5/33 utilities use grading rings at high voltage and ground end.

Dry Band Arcing

Dry band arcing can take place on polluted insulators when wetted and can lead to degrading of the insulator surface. Furthermore dry banding of an insulator can lead to flashover of the insulator under power frequency conditions.

Dry band arcing on insulators is a mechanism consisting of several steps. These steps are depicted in figure 5.2. There is however some difference between insulators, as the dry band mechanism is dependent on hydrophobicity of the surface of the rubber sheath. Both silicone rubber and EPDM are hydrophobic materials, however whereas silicone will retain its hydrophobicity, the EPDM rubber will lose its hydrophobicity. Silicone can for periods of time lose its hydrophobicity, however the silicone rubber will return to its hydrophobic state given without excessive addition of pollutants to the surface.

In the following subsections, the dry banding both hydrophilic and hydrophobic insulators will be presented.

Hydrophilic Surface

Under hydrophilic surface conditions the following pollution flashover mechanism has been observed.

The dry polluted insulator has the same voltage distribution as a clean insulator and is thus mainly capacitive. The resulting voltage stress on the insulator is non-uniform with the highest voltage stress at the line end of the insulator.

The resistance of the insulator becomes of importance when the wetting of the insulator begins (A in figure 5.2). Due to the leakage current and possible corona activity along the insulator a drying effect of the wet pollution layer will arise. As the local leakage current and corona activity along the insulator is dependent on the voltage across the insulator a non-uniform drying along the insulator will take place. The sheds or discs at the line end of the insulator dry faster than the rest of the insulator creating a dry zone on the insulator with the rest of the insulator being wet at different degrees (B in figure 5.2).

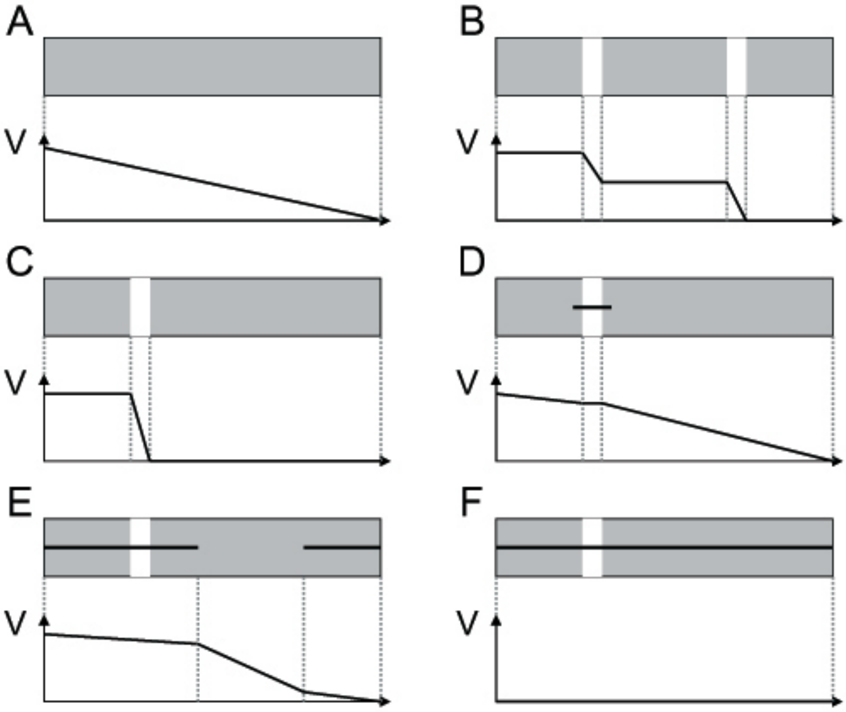


Figure 5.2: Typical steps in the dry band arcing mechanism on a hydrophillic insulator. A) Initial condition when wetting begins B) Dry bands begin to form C) Dry bands fully formed D) Dry band arcing begins E) Dry band arcing extents F) Flashover of the insulator [62] .

As the wetting of the insulator continues the non-uniform voltage distribution along the insulator increases in non-uniformity with the voltage across the dry zones increasing and decreasing along the wet zones (C in figure 5.2). At this point local arcing can occur (D in figure 5.2). The dry banding and local arcing moves along the insulator towards the earth end as the voltage across the line end of the insulator is reduced to local arcing raising the voltage gradient over the rest of the insulator (E in figure 5.2).

The flashover development can escalate to the point of flashover (F in figure 5.2) or the process can cease if the leakage current dries out the wet zone enough to linearise the voltage distribution along the insulator extinguishing arcing currents.

The process can also stop if the wetting increases to the point where the pollutants are washed away from the insulator or because the rate of wetting that the drying is stopped due to lowering of the temperature thereby prohibiting further dry zones to form. Further if the surge activity leaches the pollutants to a point where the discharge activity cannot be supported the flashover process is also stopped.

Due to the flashover mechanism being dependent on the non-uniform voltage distribution along the insulator, E-grading or corona rings which makes the voltage distribution more uniform reduce the risk of pollution flashover [29, 62].

Hydrophobic Surface

For long (transmission level) hydrophobic insulators the following flashover process takes place.

When a hydrophobic insulator is wetted by water – being from condensation, fog or rain – the water forms into drops (see figure 5.3). Some of the pollutants on the conductor surface will diffuse into the water drops making them conductive. Furthermore some of the water will enter the pollution layer on the insulator. This layer will have a high resistivity. The leakage current will reach a stable and low value when balancing occurs between the leakage current heating effect and the surface resistance reduction due to wetting.

Figure 5.3: Example of a hydrophilic insulator surface when wetted. Courtesy of Statnett SF.

The water drops, which will be scattered on the conductor surface, will react to the fluctuation in the electrical field by elongating and flattening. Furthermore the electrical field at the edge of the wet areas will rise due to low permittivity of water (see figure 5.4). The water drops may form water tracks (runnels) with following increase in the electrical field at the water drop edge. This may lead to corona discharge due to field enhancement on the insulator which can reduce the hydrophobicity locally which in turn can lead to longer water tracks.

The corona discharges will most likely take place near the live end of the insulator as the electrical field is non-uniform along the insulator and highest at the live end. Like in the hydrophilic case this will lead to faster drying of the insulator near the line end of the insulator. This increases the resistance locally and will most likely take place on the shank of the insulator as the current density is highest here, since the leakage current is

Figure 5.4: Water drop contact angle on (a) hydrophilic and (b) hydrophobic surface.

distributed over a smaller area. The leakage current is then block from running across the dry zone which lead to field concentration and possible streamer initiation. This can lead to arcing along the dry band and subsequent higher voltage stress of the wetted areas of the insulators. If the dry band is wide enough the streamer arc can develop to a flashover of the insulator [29, 62, 78, 79].

The description of the degree of hydrophobicity is not officially standardised. STRI has however published a guide on classification of hydrophobicity. The range goes from hydrophobicity class HC 1 to HC 7, where HC 1 is a surface where distinct water drops are formed and HC 7 a surface totally wetted [80].

Ageing – Silicone vs. EPDM

In the following some core difference between silicone and EPDM in their response to different exposures will be noted.

An important difference between EPDM and silicone rubber is that the surface of silicone rubber is hydrophobic and in general continues to stay hydrophobic and transfers this property to pollutants in contact with the silicone which leads to superior pollution performance. However under heavy pollution the hydrophobicity of silicone can cease to be effective, it will though return with time (24-48 hours) if the stress is only transitional. Occurrence of loss of hydrophobicity can be related to insufficient creepage distance and can thus be minimised by use of adequate creepage [29, 62, 75].

When in service silicone and EPDM will show visible changes due to the exposure to the environment. Silicone will typically show little visible change such as matting of the surface. EPDM will in contrast show discoloration, crazing and cracking which can be slight to extensive. The composition of EPDM rubber has been improved much since its introduction however the above visible changes can still be observed. The visible changes are largely cosmetic they do though lead to roughening of the surface of EPDM and thus promote water collection which increase risk of flashovers taking place [32].

The erosion of silicone and EPDM is another great difference. Silicone typically erodes through the thickness whereas EPDM erodes along the surface of the material. This can lead to different situations; erosion of silicone rubber can lead to core exposure and erosion of EPDM can lead to tracking and water collection on the insulator housing used [81].

Silicone and EDPM is the predominant choice for housing of composite insulators. However, other materials can also be found and as well as mixtures of silicone and EPDM. In [82] mixtures of silicone and EPDM are examined with regard to their mechanical and electrical characteristics. Generally silicone exhibits the best electrical characteristics (e.g. higher tracking resistance and hydrophobicity) whereas EPDM shows the best mechanical characteristics (e.g. higher tear resistance). No clear conclusions are made in which ratio the materials should be used as this is highly dependent on the environment in which the silicone/EPDM mixture is to be used [82].

The ageing and performance of housing is important but can also be difficult to predict due to the dynamic nature of rubber. How long the hydrophobicity of silicone insulators will be in effect is still a subject for discussion and examination. So far silicone insulators having been in service up to 20 years are still reported as being hydrophobic in [27] and up to 30 years in [75]. Furthermore [83] reports hydrophobicity on insulators having been in service up to 35 years which would include some of the first silicone insulators on the market. Comparisons of silicone insulators having been in service two and seven years respectively shows the same level hydrophobicity [32, 62, 83]

Factors Affecting the Dry Band Mechanism

One of the most effective measures of preventing flashover of an insulator due to pollution and dry banding, is to ensure that the insulator have a sufficient leakage or creepage distance. In IEC 60815 the dimensioning and selection of insulators are standardised for glass, ceramic and polymer insulators. The leakage distance of the insulator is also standardised here based on the site pollution severity (SPS), an indicator for the pollution level of the insulators environment. The higher the SPS, the longer the creepage distance of the insulator is required to be [84, 85, 86]. More on this topic in section 6.1.2.1.

Close spacing of the sheds on insulators can lead to increased levels of corrosion of the housing which in turn can lead to poorer pollution performance due to build up of conducting pollutants and water. Also the angling of sheds has an influence on the cleaning of the sheds with a 90 degree angle giving the least collection of pollutants over time.

The attachment of the sheds to the sheath can take place either through casting of sheath and sheds at the same time or by pulling finished sheds over the sheath, the sheds are then sealed to the sheath through vulcanisation or by use of a sealant. The later approach, with separate casting of sheds and sheath, leads to interfaces that in some cases have shown to constitute a weakness in service due to poor sealing making the shed ineffective since leakage currents can pass on the inside. Thus one piece casting of sheds and sheath is preferable [75].

Due to the better pollution performance of silicone insulators compared to porcelain and glass insulators it is frequently brought forward in literature whether or not is would be possible to lower the creepage distance (surface distance per system voltage) of silicone insulators and still receive a good pollution flashover performance.

According to [64] this has not been examined sufficiently and under all circumstances, creepage distance should not be reduced on insulators that will operate under heavily contaminated conditions. Newer literature regarding the reduction of creepage distance on composite line insulators have not been found however field tests on composite apparatus insulators lead to some interesting findings. This will be discussed further in the section below.

Experiences from Apparatus Insulators

In [87] field experience from test stations for apparatus insulators of both porcelain and silicone is presented along with experience for silicone line insulators. The test sites are generally places in coastal areas with very heavy pollution and have been in operation between 2-7 years.

When comparing the silicone and porcelain apparatus insulators the following observation was made; flashover of silicone apparatus insulators was rarer than flashover of the porcelain apparatus insulators. It was concluded that in the case of the different test locations the creepage distance on the silicone apparatus insulators could be three times as low as the creepage distance of the porcelain apparatus insulators and still have the same risk of flashover. Specifically from silicone apparatus insulators it was concluded that it would be possible to lower the creepage distance one pollution class at least compared to the recommendations for glass and porcelain insulators in IEC 60815.

Furthermore the silicone apparatus insulators were compared to silicone line insulators and some noticeable difference were found. The line insulators showed serious erosion of the surface when inspected whereas the apparatus insulators showed almost no deterioration which was the case at the four different test sites used in the investigations. The rate of deterioration for the apparatus insulators was estimated as being five times lower than the deterioration of the line insulators. Possible explanations for this are stated as being [87]:

- lower electric fields at the apparatus flanges than at the line insulator flanges – making it more difficult for dry banding activity to arise
- different location of discharge activity on apparatus insulators due to difference in flange designs – corona discharge takes place at shed edges instead of at the trunk as with line insulators
- possibly lower pollution collection on apparatus insulators due to larger diameter
- greater randomness in location of discharge activity

Flashover under Ice and Snow

Insulators have in some cases flashover while covered by ice and snow. This however is not a fully understood process as the experience is scarce.

Flashover under ice and snow usually occurs during the thawing stage – a water channel on the surface of the insulator is created and works as a high conductive channel across the insulator – the water channel has a lower resistant compared to the non-water-covered parts. The non-water-covered parts then hold a great part of the voltage to the extent that flashover occurs. This can extent to total electrical failure of the insulator. Factors such as pollution on the surface and fog or rain also reduce the insulation strength. Uneven current densities along the insulator can result in thawing of ice earlier on some part of the insulator thereby supporting the uneven voltage distribution described above.

Factors that can ensure the insulators' electrical integrity under ice and snow flashover are large spacing between sheds or increased shed diameters. Using a pollution class according to IEC60815 or creepage distance has also shown to be effective. Finally, experience have shown that V-string insulators have a better performance under ice and snow coverage than I-string insulators [29, 64].

5.1.3 Mechanical Failure Mechanisms

Overhead line insulators are subjected to different mechanical loads depending on their type and application. What is important however is which tensile forces, compression forces and bending moments that act on the insulators.

Suspension insulators will primarily be loaded with tensile forces and as the insulator can move around its mounting point, bending moments on the insulator will be limited.

For the braced line post insulator, the loads are different. For the suspension unit in the set, the forces will primarily still be tensile forces, again this is due to the unit being able to swing around its connection point to the tower. The line post unit will be subject to compression due to the conductor weight and the suspension unit. However because the suspension unit is present the bending moment on the line post insulator will be very limited compared to the unbraced line post.

The unbraced line post will have a large bending moment acting on the insulator which will cause compression forces in the bottom part of he insulator and tensile forces in the top part. The unbraced line post will have multiple forces acting in different directions and must thus handle both compression and tensile forces.

Depending on whether the braced or unbraced line post insulator is able to pivot around its mounting point, the line post insulator must be able to handle bending moment in the horizontal plane also [24].

Beside the loads in-service also loads during transportation and loading can lead to mechanical ageing. This will be presented further in the following.

5.1.3.1 Mechanical Overloading

For suspension insulators overloading is not an issue under normal circumstances since they are primarily loaded in the tensile direction where both load and strength is relatively easy to predict. Climatic loads like ice and wind could however lead to forces of unforseen sizes which must be taken into consideration to prevent mechanical overloading of insulators.

In-service, composite insulators can be subjected to bending loads. This is primarily the case with insulators of the post type which are designed to be used in situations where bending loads will arise.

Determining whether the insulator can sustain the combined load of axial and transverse load can be difficult to predict. In this case the insulator core is affected by forces in several different directions. If the combination of forces causes stresses beyond the capability of the insulator core, this could lead to buckling of the insulator. The insulator does not necessarily break into two pieces unless subjected to excessive tensile stress. This means the insulator may not fail to the point of the line being dropped, but the electrical integrity will be severely compromised [24, 64].

5.1.3.2 Transport and Handling

During transport and handling of composite insulators several different causes for damage can take place. Possible damages can lead to in-service failure of the composite insulator due to several different mechanisms leading to electrical or mechanical failure. However, the initiating cause for the failure is due to errors in the transportation and handling of the composite insulators. Most commonly errors in transportation and handling leads to exposure of the fibreglass core through breaching of housing which in service can lead to brittle fracture or water ingress leading to electrical or mechanical failure.

Some of the causes for damage during handling and transportation can be subjection of the composite insulator to bending where the core is brought to such a degree of loading that cracks or total mechanical failure arise. This could happen if a line insulator is lifted by a single point close to the middle of the insulator whereby the line insulator is bend by its own weight.

Due to the risk of bending and the risk of breaching the housing when handling composite insulators by contact with housing, it is recommend that composite insulators are handled by their end fittings.

Several causes can lead to the breaching of the housing either cutting tools when unpacking the insulators or nylon straps or rope used to lift the composite insulator (not recommended practice) are typical examples of this.

Furthermore composite insulators are too fragile to be stack directly on top of one another and must therefore be transported in crates designed with that purpose in mind.

Composite insulators in contrast to glass insulators must not be climbed or walked upon as this can lead to breaching of the housing or breakage of the core. The IEEE and Cigré guides on handling of composite insulators, [64] and [88] respectively, are excellent sources of information on this topic.

5.1.3.3 End Fitting Slipping

Cases have been reported where the end fittings of composite line insulators have slipped of the core and caused line dropping. End fitting slipping can be connected to the end fitting attachment method, where some designs have been unable to handle the everyday mechanical load. Several designs of end fitting connection to the core rod exists but will not be presented here.

According to [75] the most effective attachment method which should not lead to end fitting slipping is use of compressive fittings made in forged steel [62, 75]

5.1.4 Thermal Failure Mechanisms

The main thermal concern with composite insulators is not to exceed the service temperature range as this could lead to interface failures between the different parts of the insulator or lead to degrading of thermally sensitive materials.

General recommendation from manufacturers concerning the service temperature range of composite insulators is stated in [64] as being -50 °C to 50 °C. This is furthermore confirmed by [62] were ambient temperature limit is stated to be 50 °C.

Two apparent sources of heating of the insulator exist. The first being heating of the insulator due to heat transfer from the conductor or second due to heating by sun radiation.

5.1.4.1 Heating due to Conductor

Under normal operation conditions with conductors limited to an operation temperature of 100 °C heating of the insulator should not be a problem as the temperature will decline drastically across the line clamp and end fitting. Thereby the insulator is not exposed to high temperatures. However the question is whether this could be exceeded at high temperature operation of conductors and thus lead to failures of composite insulators due to seal failure, bonding issues or matrix/fibre interface failures [62]. No in-service experience with this could be found the searched literature [89].

In Cigré Brochure 331 it is investigated whether high temperature operating of conductors could lead to thermal issues with the line insulators. It was found that the clamp grabbing the conductor did not exceed temperature of 50 °C when the conductor was at 200 °C. The temperature of the insulator will be even lower as more heat will be dissipated along the length of the end fitting. The end fitting and the rest of the insulator should therefore be under the recommended limit of 50 °C. Furthermore the tests in [90] was carried out with normal conductor clamps. For both the ACCR and ACCC conductor armor rod grips are recommended and these would result in greater cooling of the conductor around the clamp point lowering the temperature towards the end fitting of the insulator even further [90].

Heating of the insulator due to the current carried by the conductor should therefore not be an issue as long as the recommended conductor grips/clamps – armor rod grips – are used.

5.1.4.2 Heating due to Surroundings

An overhead line insulator independent on type will be subjected to heat radiation from the surroundings. This will result in some temperature elevation of the insulator however it is expected that this temperature increase will be limited and generally not be an issue. In some climates the used of composite insulators could result in the exceeding of the 50 °C temperature limit.

5.1.5 Environmental Failure Mechanisms

Environmental failure mechanisms are caused by factors due to the environment not directly caused by the overhead line system.

5.1.5.1 UV Degradation

Composite insulators are covered by a housing protecting the core from UV light. However the housing itself needs to be UV resistant. For both silicone and EPDM (most typical housing materials) long time exposure to the sun can lead to degradation of the surface in the form of either discolouration or cracking. This does not necessarily affect the performance of the insulator. Surface cracking could though lead to water collection and thus lead to corona degrading [62].

5.1.5.2 Chemical Attack

Besides attack by chemicals that can be formed due to the electrical discharges, which can occur around composite insulators, other types of chemical attacks have been mentioned in literature though not in great detail.

Cases on distribution level have been reported with chemical attack on composite insulators where the preserving chemicals used on wood poles have migrated to the insulator surface resulting in corrosion of the rubber housing. Also railroad application of composite insulators has resulted in attack of composite insulators by diesel exhaust vapours. This can lead to swelling or corrosion of the housing surface.

Attack by chemicals not arising due to the electrical system but originating from external factors can be hard to predict. It is therefore recommended by IEEE that an expanded inspection program is included in the maintenance program if the service environment is suspected of containing chemicals that could affect composite insulators [64].

5.1.5.3 Fire

In the case of fires under the line it should be noted that the usable temperature limit of the glass-fibre/epoxy core of the insulators lies in the range 100 °C to 200 °C. Beyond this the mechanical strength of the insulator can be severely decreased and in the worst case scenario the insulator can be incinerated by the fire result in line dropping. Fires under the line could be a result of forest fires or field burning. It is not known whether field fires can sustain temperatures high enough to damage a composite insulator.

5.1.5.4 Vandalism

One of the strengths often mentioned concerning composite insulators is their vandalism resistance. The truth is perhaps not the composite insulators are vandalism resistant but rather less prone to be subjected to vandalism.

The primary form of vandalism to insulators in general is gun shot or projectile damage. Glass and porcelain insulators will shatter or splinter and the arising projectile will scatter over a wide area. This means that ceramic insulators give good visual feedback to the vandalism they are subjected to. Composite insulators will like ceramic insulators take damage from gun shots and perhaps even to a greater extent than ceramic insulators as the mechanical integrity is more easily compromised. However they will not shatter and scatter in the same way as ceramic insulators thereby given less visual feedback. This in turn have given fewer cases of gunshot damage to line insulators on lines where vandalism have been a problem [26, 62, 76, 91].

In [91] gunshot damage to composite line insulators (silicone housing) is thoroughly examined. The following conclusions were made. Damage from gunshots is clearly visible and result in damage to the core either delamination or breakage with multiple shots and rupture of the housing. The strength of a composite insulator can be degraded to such an extent – usually by multiple gunshots – that the insulator will fail mechanical by breaking. Ceramic insulators were also tested with respect to gunshot damage response and it was found that a single shot in general only resulted in a small reduction of the mechanical strength. However multiple shots could, as with the composite insulator, lead to complete breakage of the ceramic insulator. In some cases severe reduction of mechanical strength was the result instead of complete failure. However the ceramic unit showed greater resilience to multiple gunshots than the composite insulators tested.

In [91] composite post insulators were also tested with regard to their response to gunshot damage. Composite post insulators showed no significant reduction in the mechanical strength contrary to the line insulators, even with multiple shots to the post insulators.

Insulators damaged by gunshot can lead to different failures. For ceramic units gunshot damage leading to failure can either be mechanical or electrical (cannot hold the system voltage). Composite insulators usually fail mechanically leading to conductor dropping while electrical failures have not been reported. No cases of failure where mentioned in [91].

With small firearms that could perhaps be a problem with inspection, as these do not lead to clear damage to a composite insulator. This could lead to internal tracking in the insulator and result in electrical failure of the insulator. The influence on the rate of ageing of gunshot damage is not fully known and needs to be investigated further [91].

Composite insulators are also vulnerable to cutting which could lead to exposure of the core. However vandalism including cutting can only take place while the insulators are not in-service or during storage of the insulators. This must be considered to a very rare occurrence and should be not be able to take place if proper precautions are taken [64, 88].

5.1.5.5 Animal and Insect Attacks

Reports have been made of bird and rodent attack on composite insulator which have not been an issue with glass and porcelain insulators. Bird and rodent attacks can lead to reduction of creepage distance and exposure of the core rod. This has only been reported as an issue is very few areas and usually where large birds like parrots are present [62]. Not only in-service but also under storage can composite insulators be subjected to attacks by rodents. Examples of this can be found in [64].

5.1.5.6 Biological Attack

Reports of mould growth on rubber insulators have been reported in some cases where insulators are located in humid environments. In [92] the effect on the insulation strength of mould growth on rubber insulators is investigated and also whether the mould growth consumes the rubber.

It was concluded that the mould did not seem to alter the rubber material. Furthermore only some of the silicone insulators had mould growth which could indicate that it is not the silicone material but additives that support mould growth. It could not be concluded which housing material type (silicone or ethylene propylene rubber – EPR) is best to inhibit mould growth.

Thus mould growth can take place on silicone insulators given the correct environment. Mould growth will reduce the hydrophobic characteristics but the insulator will still be less wettable than EPR insulators and thus performer better under contaminated conditions. The EPR insulators did not exhibit mould growth. Suggestion for removing mould growth is given in [92].

5.1.6 Analysis of con's and pro's

In the following section the advantages and disadvantages of composite insulators will be discussed. It should be noted that several different designs and ways of assembly exist or have previously been used for composite insulators. A thorough description of experiences with different insulator designs can be found in [76]. An important conclusion of the work carried out by Maxwell et al. is that many of the issues experienced with composite insulators are related to the design rather then the properties of the applied materials.

5.1.6.1 Design and Performance

Performance of modern composite insulators is primarily dependent upon design and quality and not materials properties. Many of the failures can thus be avoided by learning from present experiences and recommendations [69, 76].

Good in-service performance is very dependent on quality and process control as well as correct handling of insulators both during manufacturing as well as under transportation and installation. In spite of the many possible failure mechanisms of composite insulators a Cigré survey from 2000 showed that the average failure rate of composite insulators is comparable to glass and porcelain insulators [26].

5.1.6.2 Failure Rate

According to [77] the failures registered with composite insulators are mainly on insulators of older date belonging to early generations. Presently insulators on the marked are referred to as the third generation and much experience from previous generations have been incorporated into modern composite insulators.

In a Cigré survey from 2000 on service experience with composite insulators [26] it was indicated that over 690.000 composite insulators are in service at voltage levels above 100 kV worldwide. Of these 690.000 insulators 243 failures were reported (failures are defined as that the insulator cannot hold the mechanical load or cannot hold the specified voltage), which corresponds to 0.035 % failed in service. In the survey this is reported as corresponding to 0.52 failed insulator(s) per 10,000 insulators per year. For the US a value of 0.59 failed insulators per 10,000 insulators per year. For cap and pin insulators (glass insulators) the number is 0.5-1.5 failed insulators per 10,000 per year. The failure rate for porcelain insulators is reported as being in the same range as for glass cap and pin insulators.

It should however be noted that direct comparison of these number does not give a picture of which insulators types are to be preferred. This is due to that for composite insulator failures may be more severe than for glass cap and pin insulators such as total electrical failure where as glass insulator can sustain voltage even if one or more units in the string has failed. Furthermore line dropping may be more predominant with composite insulators. Another factor to take into account is that the failure rate for composite insulators will most likely be reduced as older insulators of the first generation is replaced by third generation. More first generation insulators are in service in the US which could explain the higher failure rate compared to the Cigré survey.

For composite insulator in service above 300 kV the failure rate is estimated as being 5-10 times higher than for composite insulators in service below 300 kV. 8.5 % of composite insulators are in service between 300 kV and 500 kV. No indication as to why this is so is given in the survey. However, a cause for this could be the apparent lack of use of grading rings compared to recommendations which could lead to several different kinds of failure, see section 5.1.2.2 for more.

5.1.6.3 Maintenance – Cleaning

Generally speaking composite insulators are maintenance free but insulators being used in heavily polluted areas are often cleaned to ensure a continued good pollution flashover performance. Composite insulators can also be cleaned by conventional methods which usually consist of high pressure washing or air blasting.

Whether or not a composite insulator can be high pressure cleaned depends on its design. Some insulator design can be susceptible to water or air ingress at interfaces when subjected to high pressure. The manufacturer should be consulted to find out if high pressure cleaning of the insulator in question is advisable [64].

Due to the ability of silicone rubber to transfer its hydrophobicity to pollution on its surface, it is often stated in literature that silicone composite insulators due to this ability does not need cleaning [75].

5.1.6.4 Inspection

Composite insulators should be inspected with regular intervals to detect possible degradation or damage to units. Damage units should be replaced as soon as possible. Units with minor degradation or damage to the sheds can often continue in service with no serious reduction in its electrical or mechanical performance and can even be repaired in field [30, 64].

Compared to glass insulators, composite insulators can be harder to detect damage on by visual inspection. The glass of glass insulators will shatter if damaged whereas composite insulators due not shatter. Composite insulators will often only have local damage unless being subjected to severe damage. Often composite insulators must be closely inspected to detect damage to the insulator in example breaching of the rubber housing or seals. Inspection usually takes place from the ground however in [91] it is indicated that inspection by use of binoculars is sufficient to inspect for gunshot damage. Breaching of seals or the housing however can still pose a problem [64].

Several other methods of inspection have been developed for line insulators and composite line insulators. These include sonic, thermal and corona based inspection methods. These methods will not be presented or discussion in the present Thesis [13].

5.1.6.5 Life Expectancy

Composite insulators having been in operation since the nineteen seventies can still be found on overhead lines. Since this first generation of was introduced to the market many advances have been made within composite line insulators. Today the expected life of composite insulators are around 40-50 years, which is comparable to glass-insulators. It should be noted that it is still recommended that regular inspections of composite insulators should take place throughout the insulators life time [29, 74, 83].

5.1.6.6 Summery Comparison of Composite and Ceramic Insulators

Based on the previous presented information, a comparison of composite insulators to glass and porcelain insulators is made in table 5.2.

Some of the advantages of composite insulators are that they are light weight and at the same time mechanically strong under tensile and compressive loads compared to glass and porcelain insulator. Furthermore silicone insulators out perform glass and porcelain insulators with the same creepage distance with respect to pollution flashover. However there are also some disadvantages of composite insulators compared to the more conventional ones. Among these are that composite insulators are not easily inspected with regard to failure development. Here glass units have the advantage of being easily inspected when an error have a occurred and that the rest of the glass disc string performs well despite the failure of up to several discs.

Table 5.2: Comparison of composite, porcelain and glass insulators [29, 42, 64, 87, 93].

	Glass (cap and pin)	Porcelain (long rod)	Composite (long rod)
Advantages	High mechanical capability High impact and bending capability of string Ease of visual inspection	Puncture proof High mechanical reliability High electrical reliability Very low maintenance requirements Lower weight than glass cap and pin insulators Ease of visual inspection	Low weight Hydrophobic surface – superior pollution performance (silicone) Slim profile Flexibility Less prone to vandalism Puncture of sheds has low electrical effect
Disadvantages	High electrical stressing of the insulating material Risk of electrical puncture Susceptible to corrosion due to numerous fittings High weight of insulator sets High maintenance costs	Expensive production Low mechanical impact strength Design of insulator sets regarding dynamic load Less frequently adopted outside Europe and Middle East	Mechanical sensitive silicone surface High technical production efforts Sensitivity to aging Can be sensitive to high pressure washing Inspection issues

5.2 Overhead Line Conductors

Overhead line conductors are the transport corridor of the system and are therefore when in-service at full voltage potential and carry the current flow in the overhead line system.

Furthermore they are subjected to different mechanical loads arise due to snow or ice on the conductors or wind blowing the conductors out in an angle to vertical. Wind can also start Aeolian vibrations on or galloping of overhead line conductors leading to fatigue.

Thermal affects on overhead line conductors will also arise either due to heating by the current running in the conductors or due to heat exposure to the surrounding environment.

Finally the external environment can influence the performance and ageing of overhead line conductors in several ways including UV exposure, salt and chemical corrosion.

All these and more environment effects on overhead line conductors will be examined in the following with respect to the performance of composite based overhead line conductors.

5.2.1 Failure Modes of Overhead Line Conductors

Overhead line conductors should transport power without exceeding minimum clearances to the general public and nearby objects. Based on this the general failure modes of overhead line conductors are breakage of the conductor, a mechanical failure also leading to the inability to transport power along the conductor, or excessive sag of the conductor whereby clearances are exceeded.

5.2.2 Electrical Failure Mechanisms

Overhead line conductors are designed to carry power at a wide range of voltage levels and they can carry several kA dependent on the use of subconductors. Conductors are not subjected to an electrical field internally and the surface electrical field gradient is primarily interest with regard to audible and radio noise and to as such not cause any noticeable damage to the conductor under normal circumstances.

5.2.2.1 Lightning Termination on Conductor

Lightning terminating on overhead line conductors can cause local melting of the aluminium of the conductor. This also applies for composite based overhead line conductors. Termination of lightning on conductors and subsequent melting of the aluminium can lead to breakage of the aluminium strands.

Breakage of some of the aluminium strands will result in a small reduction of strength of the conductor but this should not lead to mechanical failure of the line due to large gap between conductor strength and normal loading stresses. For conductors like the ACCC using annealed aluminium, breakage of the aluminium strand will have no effect on the conductor strength [42, 62].

5.2.2.2 Short Circuit Currents

Two concerns regarding short circuit currents on composite conductors are the temperature of the conductor's core and the risk of bird caging.

Short circuit currents can arise on conductors due to faults in the electrical system thereby subjecting the overhead lines to several tens of kA in a very short time span (< 1 s). The short circuit currents will increase the temperature of the composite conductor subjected to the fault current. This could lead temperature above the recommended values for the conductor or lead to bird caging of the aluminium conductor due to differences in the thermal expansion coefficients of aluminium and the composite core.

These two issues will be examined more closely in the following sections.

Conductor Core Temperature

The allowable temperature rise of composite conductors under short circuit currents is not fully examined and no standards have been found were this has explicitly been specified. The risk is that the composite conductor or aluminium conductor will be damaged or partially melted due to rise in temperature under short circuits. However the consequences are not fully known even though manufacturers of composite conductors have made several test reports available to uncover the potential risks [41, 94, 95].

For both ACCR and ACCC composite conductors short circuit test have been carried out to try and determine the temperature affects on composite core [94, 95].

Generally both ACCR and ACCC are cooler than ACSR conductors of the same diameter. This is for both ACCR and ACCR due to that the conductors do not have a ferrous core thereby generating less heat (ACCR) or no heat at all (ACCC). The ACCR conductor will generate less heat as the core is made of an aluminium composite that is more conductive than steel. For the ACCC conductor there will not be generated any heat in the core as the short circuit current will only run in the aluminium conductor. The cores can though be more vulnerable to heat than the steel core of the ACSR conductor [94, 95].

For ACSR conductors a maximum temperature of a conductor under short circuits is recommended to be 200 °C. It has been indicated that the same value should be kept for composite conductors which would seem reasonable, especially for the ACCC conductor which could degrade at higher temperatures of the core [46].

It is important to keep in mind that composite conductors are not only capable of replacing ACSR conductors but also to run at higher temperatures than ACSR conductors under normal operation conditions. Thus faults occurring under high loading conditions could results in temperature beyond 200 °C of the conductor and core leading to damages on the core of the conductor. Effects of short circuit current on composite conductors, especially ACCC conductors, need to be considered when designing the line to ensure that the core of the conductor is not damaged due to high temperatures [41, 46].

Bird Caging

Bird caging of conductors is a phenomenon that makes the aluminium strands or wires on the conductor form a bird cage like shape around the core of the conductor. An example of bird caging can be seen in figure 5.5. The bird caging arise due to the differences in thermal expansion of the core and aluminium. The aluminium will expand quicker than the core and can go from being in tension to compression if the differences in expansion are great. Bird caging have been found on ACSR conductors in-service. As of yet no reports on bird caging of ACCC or ACCR conductors have been made. However, since both the core of ACCC and ACCR conductors have a lower thermal expansion than steel thereby making the difference in the thermal expansion coefficient even greater than for ACSR, it should be expected that sooner or later examples of bird caging ACCC and ACCR conductor will be found [41].

In test reports [94] and [95] bird caging on ACCC and ACCR conductors are examined. Bird caging did arise on the tested conductors at high short circuit energies. At which point bird caging would arise on the conductors is dependent on the cross section or diameter as bigger conductors can absorb more energy than small conductors thereby bird caging at higher short circuit currents. However it would seem based on the test reports that ACCC and ACCR will experience bird caging in the same range as ACSR conductors.

In [94] it was observed that bird caging only took place on conductors being at low load stage (corresponding to a conductor temperature of 40 °C) when the short circuit current was applied. For conductors at high loading (corresponding to conductor temperature of circa 150 °C) bird caging did not arise. It would therefore seem that a sufficient temperature rise is needed before bird caging can develop on a conductor.

Bird caging arising on overhead lines is usually not a big problem since the line can remain in operation. The core will simply take the full mechanical load. The segment of the conductor where bird caging have happen should be replace to ensure that no problems will arise with time. This is a straight forward process for ACSR conductor and similar methods of line cutting and joining can also be used for ACCC and ACCR conductors with special designed joints. Due to the special core of the ACCC conductor special joints must be applied [43, 48].

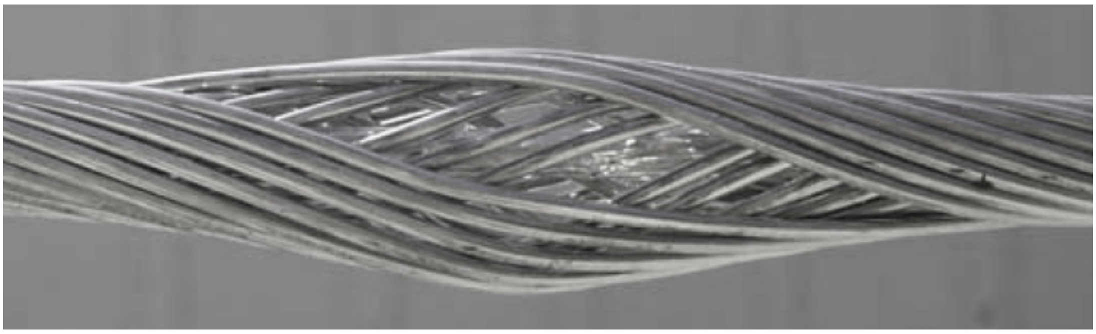


Figure 5.5: Birdcaging of a 477 kcmil (242 mm^2) ACCR conductor after short circuit current test [94]. Courtesy of 3M.

Normally bird caging is not an issue on overhead lines as it can be easily detected by visual inspection from the ground and a conductor having bird caging can easily continue its operation with the bird caging present. The concern is that when bird caging arises on a conductor, the core of the conductor will be exposed to the elements. For ACSR conductors this can result in corrosion of the steel core this is though a time demanding process. For composite conductors, especially ACCC conductors, several other failure mechanisms can be initiated once the core has been exposed and thereby accelerate the aging of the conductor (sun light exposure and corona exposure).

5.2.2.3 Corona under Power Frequency Voltage

Overhead line conductors in-service will operate at full voltage potential (though with a voltage drop along the line). Concern have been express with composite conductors due to this and when considering operation experience with composite line insulators with regard to electric fields under power frequency voltage. For ACCR conductors which consists of a ceramic matrix with metal fibres no concern have been expressed however with ACCC conductors, with an epoxy matrix core with glass/carbon-fibre reinforcement, concern have been expressed with regard to tracking and the risk of brittle fracture.

Corona exposure of the core could lead to the formation of nitric acids and ozone leading to degradation of the conductor. The aluminium is not vulnerable to nitric acids or ozone but the glass fibre part of the core is. If the fibre glass core is attacked this could lead to brittle fracture of the glass fibre part in the same manor as with composite line insulators. How the carbon core will react is not known. In the best case it will be unharmed as the nitric acids normally attack the glass fibre and not the matrix material. Corona exposure of the core is though not very likely to take place but could happen if the conductor is damaged and the aluminium brakes leading to aluminium end points near the fibreglass surface where corona could arise. However this would easily be seen under a visual inspection.

Normally corona will be limited to the conductor surface (due to surface gradients) and not affect the core. However it has not been examined in the available literature whether nitric acids can migrate into the conductor to the conductor core leading to degradation of the fibreglass part of the core. Near the core though the electric field should be near zero as the electric field is zero within a conductor. Therefore corona will not arise at the interface with the core. Furthermore the development of tracking, in spite of the low tracking resistance of fibreglass, is also unlikely as the electric field along the axis of the conductor is near zero.

Due to the zero or near zero electric field it is also very unlikely that interface issues inside the conductor – between aluminium and fibreglass and between fibreglass and carbon core – will arise as these are normally field related [41].

5.2.2.4 Corrosion Fracture

The cores of composite based conductors are very different both in structure and materials. Thus operation experience with one type of conductor does not necessarily tell much of the expected performance of another type of conductor with respect to the core.

ACCC conductors could be – as composite insulators – subject to fracture due to corrosion of the core. This is not the case with ACCR conductors as the aluminium oxide core is more resilient to chemical attacks [41, 96]

Due to the suspicion that corrosion fracture can occur on composite conductors of the ACCC type, a test corresponding to the brittle resistance test on composite insulator cores were carried out in [97]. Samples of the ACCC core (consisting of boron free fibreglass covered carbon fibre imbedded in epoxy) was subjected to a 25 % rated tensile strength load while exposed to either a 1 N or 5 N HNO_3 solution (nitric acid), at test normally applied to test fibreglass rods resistance to brittle fracture. For the core to be classified as brittle fracture resistant is must maintain its strength after 96 hours of exposure to the 1 N solution. After 11 days (264 hours) of exposure to 1 N HNO_3 solution the tensile strength of the conductor core was found to be 125 % rated tensile strength. For the piece in the 5 N HNO_3 solution the tensile strength was found to be 108 % rated tensile strength after 96 hours of exposure and slight frying of the surface was visible. Thus the core of ACCC conductor is brittle resistant and shows good resistance to chemical attack in test [97].

Whether thermal ageing of the core could affect the brittle resistance have also been tested. A sample of the core was left for 18 weeks at 200 °C and then subjected to a 1 N HNO_3 solution for 120 hours. The tensile strength of the sample after the nitric acid exposure was tested as was the tensile strength of a sample that was only thermally aged. Both samples showed a tensile strength of 95 % rated tensile strength. This test also indicates the ACCC core's abilities of resisting brittle fracture [98]. The thermal aging was in this case severe and will be discussed further in section 5.2.4.1.

In [97] carbon fibre, boron-free glass fibres and boron-containing fibres glass fibres was left for twelve days in a 1 N NHO_3 to examine the affect on the fibres. Only the boron-containing fibre showed micro-structural damage. The boron-free fibres showed surfaces changes but no micro-structural damages. The carbon-fibres did not have any damage.

For the ACCC conductor, boron-free glass fibres are used to ensure resistance to chemical attacks and this would seem to ensure a good mechanical and electrical performance. For ACCR conductor nitric acids should not pose a problem to the integrity of the conductor as the conductor is chemically stable [96].

5.2.3 Mechanical Failure Mechanisms

Overhead line conductors are subject to several different mechanical loads. These include cold load, ice load and wind load where the conductor is stressed in different manors. Beside these loads of static nature are also dynamic loads such as Aeolian vibration and galloping which can result in cyclic fatiguing of the conductor.

5.2.3.1 Overloading

Conductors when installed are strung at a certain tension resulting in a mechanical stress in the conductor. The stress is however dependent on several factors such as the conductor temperature and weight. Furthermore, with time the and loading history, the conductor will elongate, reducing the stress in the conductor. These factors needs to be considered when designing the overhead line, to ensure that the conductors is not loaded beyond its capabilities and that required clearances are kept. If conductors are overloaded the aluminium wires and core will break resulting in mechanical as well as electrical failure of the conductor.

As stated conductors will elongate or creep with time resulting in greater sags than at the time of installment. This also applies for the ACCC and ACCR conductors though the cores of the two conductor types due not creep with time and thus the creep of ACCC and ACCR conductors are caused solely by the aluminium. For the ACCC conductor this should not have an affect on the sag since only the core carries the mechanical load

[46, 89, 96].

Two factors can lead to high stresses in a conductor. These are cold load (low temperatures) leading to contraction of the insulator and thereby increased conductor tension and ice loads, which can result in drastic increase in the weight of the conductor and thereby increased conductor tension. If these factors are not included in the design of the line, they can lead to high stresses of the line and conductor breakage if the strength of the conductor is reduced [42, 99, 100, 101, 102]. These factors will be examined closer in section 6.2, where sag, tension and current relationship of conductors are presented.

5.2.3.2 Excessive Bending

Overhead line conductors are normally loaded primarily in the axial direction. Under installation of overhead conductors they can be subjected to bending forces that can result in damage to the conductor.

Excessive bending forces can arise if the minimum bending radius is exceeded during installation. This can take place if to small reels or exit angels are used.

For ACSR conductors excessive bending of a conductor can results in slipping or breakage of the aluminium strands on the conductor. This will then result in the need for replacing a section of the conductor around the damaged area unless larger sections of the conductor are damaged. The same can happen for ACCR conductors which have similar requirements for minimum bending radii of the conductors as ACSR [48].

For ACCC conductors minimum bending radii as for ACSR conductors have to be kept. The consequence are however more severe for ACCC conductors than for ACSR and ACCR conductors as some cases of in-service breakage of the conductor have occurred due to breakage of the core during installation. The reported cases of conductor breakage can all be linked back to excessive bending during installation. Three cases of conductor breakage are reported in [44, 46, 103].

5.2.3.3 Cyclic Fatigue – Aeolian Vibrations and Galloping

No reports of cyclic fatigue of composite conductors in operation have been made however only very short term operation experience with composite conductors has been made so far [89].

Furthermore test have shown that trapezoidal shaped wire conductors are better at resisting Aeolian vibrations as these have lower point-to-point pressure as they have a larger contact surface between the different strand of the conductor [46].

In general it is recommended to follow the same practise for composite conductors as established for ACSR conductors though it must be ensured that the tension limits are based on tension and not percent rated tensile strength as this would result in high tensions in composite conductors due to their high rated tensile strength and could result in increased risk of Aeolian vibrations. The individual conductors' mechanical characteristics are only important in cases where dampers are not used. In Denmark dampers are generally used on overhead transmission lines however national preference with regard to this varies [46, 104].

Test of cyclic fatigue have been carried out on the ACCC conductor by the manufacturer. The conductor was subjected 100 million cycles to simulate Aeolian vibrations. After the cyclic exposure the breakage strength of the conductors was measured to 102.4 % rated tensile strength indicating a good Aeolian vibration resistance since the strength is above 100 % rated tensile strength. The breakage of the core took place at mid span. Similar results are reported in [105] however here one of the end fittings failed in test. The conductor it self stilled showed good performance with respect to Aeolian vibrations [105, 106].

In [107] test of carbon fibre's cyclic fatigue resistant shows that the fibres after exposure the cyclic action showed slightly larger Young modulus or elasticity modulus. It was concluded that carbon fibres showed good fatigue resistance due to cyclic loading, also indicating that ACCC conductors should perform well with regard to fatigue.

It has been reported that the ACCR conductor along with hardware have been tested for Aeolian vibrations. The conductor shows less microstrain than ACSR conductors both with and without dampers indicating a better performance. It was concluded that the ACCR conductor is robust against galloping and Aeolian vibrations. Furthermore dampers can effectively be applied to ACCR conductors against Aeolian vibrations [96].

An investigation into the cyclic fatigue performance of selected fibres indicated that Al_2O_3 fibres could experience mechanical failure at loads well below the predicted tensile strength due to the development of micro cracks present in the fibres from the manufacturing process. This has lead to the fear that ACCR conductors could suffer from micro cracks in the core due to Aeolian vibration action [107]. However the test referred to above reported above would indicate otherwise. In-service report of micro crack failures have not been made for ACCR conductors however this could also be due to the limited experience with respect to time in service.

5.2.4 Thermal Failure Mechanisms

The thermal degrading of materials is related to the temperature of the conductor. However the temperatures to which the materials in overhead line conductors are subject to degradation will not arise unless the conductor is loaded. Thus the actual cause for the degradation of the material is the current carried by the line and the resulting temperatures. It could therefore be argued that the following section should be placed under electrical failure mechanisms and not thermal failure mechanisms.

5.2.4.1 Thermal Degradation of Materials

A major difference between the ACCC and the ACCR cores is that the first core is organic and the latter inorganic. The ACCC core is thus more sensitive to temperature though it still allows operation of the conductor at 180 °C (200 °C). However investigations have shown that at temperatures above 300 °C the core will lose weight (deteriorate) rapidly which could deteriorate the mechanical strength. This is not the case with ACCR conductors. Furthermore it is indicated that already at around 150 °C the ACCC conductors start to be affected by thermal ageing [41].

This is in part supported by a thermal test carried out by the manufacturer. In the test the ACCC conductor was placed in a 200 °C hot oven for 18 weeks and afterwards tested with respect to tensile strength which was at 95 % RTS. This test is severe considering the 18 weeks exposure, however over the conductor's life time, loading at high temperatures could happen for a combined long time. However the high temperature exposure of the core is very dependent on the application of the line and high temperature loads could be limited to emergency operation only [98].

The fibres of the ACCC core are stable up to 500 °C, yet the matrix is only able to operate at temperatures up to around 200 °C. The annealed aluminium of conductor can operate under temperatures up to 400 °C [46].

In [108] the glass transitions temperature of the epoxy core of the ACCC conductor is tested. It was found that the glass transition temperature is circa 215 °C. This is the temperature where the epoxy will go from a glassy state to a liquid state and thus beyond the glass transition temperature the epoxy will no longer be able to function as a matrix.

Under normal operation of ACCC conductors this should not be an issue however it is unknown if the core could experience temperatures above 300 °C under short circuit conditions where the current in the conductor can be raised to high levels in very short time. It is recommended that the ACCC conductor is only operated in the temperature range 180-200 °C up to 5 % of the time during a life time of approximately 50 years [46].

Test of the temperature stability of the ACCR conductor have also been reported in literature. It was found that after 300 hours at high temperature and cyclic current loading that the conductor retain full tensile strength and the hardware had 99 % rated strength. The ACCR conductor would not seem to experience any noticeable degrading at the temperature recommended by the manufacturer [40, 89]

5.2.5 Environmental Failure Mechanisms

Overhead line conductors are subjected to many different exposures in service. In the following these will be presented along wit any failure mechanisms the environment may cause.

5.2.5.1 Corrosion due to Salts

For ACSR conductors, salts deposited on the conductor, which is dissolved by water during rain, can lead to corrosion of the steel core. This can especially be a problem in heavily salt polluted environments. Often this is counteracted by greasing the conductor thereby sealing the core from salty solutions.

The ACCR conductor have been applied on a line on Hawaii for several years without any signs of corrosion beyond what can expected on the surface of the conductor thus no corrosion of the core have been detected [96].

The ACCC conductor have by the manufacturer been subjected to salt corrosion test and showed no signs of deterioration whereas an ACSR conductor tested along with the ACCC conductor did show signs of deterioration [109].

For ACCC and ACCR salt should not pose a problem.

5.2.5.2 Alchemical Corrosion of the Core

The ACCC core consists of a carbon-epoxy core protected by a fibreglass-epoxy layer (see 4.6). The fibreglass layer ensures that the aluminium conductor and the carbon core do not react and thereby degrade the mechanical strength of the carbon core. If the fibreglass layer is breached degradation of the carbon core and ultimately failure of the core is likely to take place both through reaction with the aluminium layer but also as a result of corona degradation of the core as is well known from fibreglass rod insulators. Alchemical corrosion due to reaction between the aluminium and carbon can only take place if the aluminium and carbon are in direct contact and should therefore not pose a threat in operation. Reported tests on the ACCR conductor did not show signs of deterioration due to corona [41, 110].

5.2.5.3 UV Exposure of Core

Normally UV radiation of overhead line conductors does not present a problem with regard to the electrical and mechanical integrity of the conductor. For the ACCR conductor it stated by the manufacturer that the conductor has long term stability to UV.

For the ACCC conductor which contains an organic composite UV exposure could represent a problem. However this is only if the core is exposed to direct UV radiation. Normally the core will be protected from UV exposure by the aluminium strands. The manufacturer has conducted tests concerning UV ageing of the core. However no standardised test for overhead line conductors exists therefore the conductor core have instead been exposed to normal sun light for 324 hours over 27 days in a high exposure period. After the exposure to sunlight the tensile strength was intact however the glass transition temperature was reduced from 206 °C to 194 °C [111]. This would indicate that the

ACCC core is vulnerable to direct sunlight however the degradation process is slow and does not result in a severe reduction of the mechanical or electrical strength at normal temperatures. The most likely way of the core becoming exposed to sun light through birdcaging of the conductor whereby the core is no longer protected by the aluminium at the point of birdcaging. This could however be detected by visual inspection and would due to the bird caging result in exchange of the exposed part of the conductor.

5.2.6 Analysis of con's and pro's

In table 5.3 the ACCC and ACCR conductors are compared to conventional ACSR conductors and the advantages and disadvantages are listed. The comparison are based on the previous this and previous chapters.

Table 5.3: Comparison of ACCC and ACCR conductor types to ACSR conductor.

	ACCC	ACCR
Advantages	Light core High temperature range Very low thermal expansion	Light core High temperature range Low thermal expansion of core
Disadvantages	2.5 x price Mechanically vulnerable core Temperature sensitive core	10 x price

One clear disadvantage of both the ACCC and especially the ACCR conductor types are their price. These conductors given the same conductor diameters costs from 2.5 to 10 times as much as an ACSR conductor. This have resulted in that these conductor types are explicitly used for uprating of already existing overhead lines and not for new projects since the choice of conductor is more free in the design period making it more attractive using less expensive conductors keeping the total project costs down.

5.3 Towers

Composite based towers for overhead transmission lines are not widely used. The use of composite towers in overhead line systems primarily takes place in the USA and service experience is rarely mentioned in literature. The service experience mentioned here is mainly based on distribution overhead line system.

The available literature only indicates very few issues with composite based towers. Issues reported are related to UV degradation of the composite material causing blooming in the outer layers of wall material. Composite towers were developed for the hard marine environment on Hawaii where wood experienced great degradation and steel heavy corrosion. Composite towers with UV resistant coating have been applied in this environment since the 1960s and good service experience has been reported.

5.3.1 Failure Modes

The purpose of a tower is purely mechanical ensuring that overhead line conductors and insulators are mechanically supported. Thus failure of towers would be the inability to support overhead line conductors and insulators at the designed geometry.

5.3.2 Electrical Failure Mechanisms

Of an electrical nature very few issues can be found with composite towers. The main concern would be how lightning transients hitting ground wires can be conducted to ground and whether these lightning currents can affect the structural integrity of the composite towers.

5.3.2.1 Lightning

Towers of overhead line systems can be subject to lightning impulses if lightning strikes hit the overhead line ground wire(s). The lightning impulse will be conducted along the ground wire and parts will also be conducted towards ground through the towers of the line – however only if the ground wire is not insulated from the tower and if the tower is conductive.

Steel towers are conductive and is normally used to connect the ground wires to earth potential. Thus steel towers will carry a current if the ground wires are struck by lightning. Wood poles are nonconductive and will not carry a lightning current if struck by lightning. Wood poles can however be equipped with a down–conductor to connect the ground to earth and to allow the lightning current impulse to be conducted towards ground [42].

Composite towers are normally made of insulating composite materials (see section 4.1.3) and are thus like wood poles nonconductive. However to facilitate earthing of the ground wire some composite pole manufacturers can supply composite towers/poles with attachments for a down-conductor [60].

However due to the high lightning current that can be conductor to earth it is possible that the composite material tower will have charring or burning at the attachment points of the down-conductor. However this has not been reported as a structural concern but is only an aesthetic concern [60].

5.3.3 Mechanical Failure Mechanisms

Failure mechanisms caused by mechanical effects are primarily related to in-service load. However also damages caused under installation or transport can lead to the mechanical ageing of towers. In the following these two sides of tower failure mechanisms will be presented.

5.3.3.1 Overloading

Overloading of towers is normally not a concern since they are designed to be able to handle forces greater than those that will happen under normal loading. These loads that are considered are loads due to wind forced on the towers, conductors and insulators resulting in mechanical loading of tower. Further more also ice accretion must be considered as this will also increase the forces on towers in an overhead line system. Beside these climatic loads the tower structures must also be able to handle the forces and bending moments that can arise in case of conductor breakage. All these factors are included in the European standard for overhead line design (EN5341) [99].

It should be noted that ice and wind loads beyond those recommended in EN50341 could occur resulting in severe loading of tower structures and possible failure of towers. If not loaded beyond the point of failure composite towers will return to their original position/shape since they are fully elastic until the point of failure. Steel towers will have a plastic zone before failing but will however require repairs or replace after the excessive loading event [24, 61].

Composite poles are repairable though dependent on the amount of damage. Repairs of composite poles can either be done through application of resin to the damaged area or by applying fibre mats around the point of damage with subsequent application of resin [60].

5.3.3.2 Transport and Handling – Notches and Scratches

Superficial notches and scratches inflicted during transport, installment or operation are not considered as having any significant impact on the structural integrity of composite towers. However deep tears could lead to reduction of strength and stiffness of the tower and should be repaired [60, 112].

5.3.4 Thermal Failure Mechanisms

No real issues with thermal degrading of towers. They are only subjected to temperatures due to the surroundings. Compare to cores of insulators, towers should thus be able to operate in the range of -50 °C to +50 °C without any degradation of the towers mechanical strength.

5.3.5 Environmental Failure Mechanisms

Composite based towers or poles are primarily at present seen as an alternative to wood poles. In the following many of the environmental failure mechanisms mentioned are related to wood and not to steel as primarily used in EHV overhead line systems.

5.3.5.1 UV Degradation

Sun radiation and the resulting UV exposure of towers can lead to degradation of the composite material. The damages can be fibre blooming and visual discoloration. Visual discoloration is purely a cosmetic problem while fibre blooming could lead to mechanical degrading of the composite material. This however has not lead to in-service mechanical degrading of the tower. Furthermore coating of UV sensitive towers can prevent degrading with only reapplication of coating every twentieth year. Towers made with UV resistance composite wall material have recently become available and these towers do not require coating and thus need less maintenance [53, 57, 60].

5.3.5.2 Biological Attack

Unlike wood poles, composite based poles are susceptible to biological attacks. This include rod, which is a problem with wood poles. The composite materials used in fibreglass based poles are environmentally inert and will therefore not degrade due to biological attack nor will the tower pollute the surrounding environment with toxins [53, 55].

5.3.5.3 Animal and Insect Attack

Composite poles are unlike composite insulators not susceptible to animal or insect attack. This has proven to be a large advantage compare to wood poles at distribution level [53].

At EHV levels where steel towers are most often used, the only problem reported with respect to animals are birds and bird nests reducing clearances between phase conductors and the tower structure.

5.3.5.4 Salt Corrosion

Unlike both steel towers and wood poles, composite based poles are not subject to salt corrosion. This was the reason for using composite based utility poles on Hawaii where the very salty environment made used of wood and steel less preferable than composite poles [53].

5.3.5.5 Fire

Not much information is available concerning the fire resistance of composite based towers. However it must be expected that composite towers can be subjected to fires either due to field burning or forest fires which over overhead line pass over or through.

The composite materials which have typically been used for composite based poles – epoxy based fibreglass – is however flammable and will therefore at high enough temperatures burn. It is however possible during the fabrication process of composite poles to include fire retardants in the material mixture thereby increasing the fire resistance of composite towers. In [113] it is reported that a test composite pole survived a fire that claimed over 3,000 wood utility poles.

5.3.5.6 Impacts

Impacts to towers can happen under different situation. This could be by vehicles or objects hitting the tower by accident but also intentional impacts on towers could be imagined [59].

One manufacturer report that due to lightness of the towers, the conductors can support the tower mechanically in the case of a major impact that breaks the tower and makes it unable to support the line. This accounts for utility poles, but due to the light weight of composite based poles and towers this could also be the case at EHV. This does however require investigations beyond the scope of the present work [58].

5.3.5.7 Vandalism

Based on section 5.1.5.4, 5.3.3.2 and 5.3.5.6. Vandalism to composite based towers should not present a problem with regard to the mechanical integrity of the tower. Compared to hollow core insulators where gunshots was reported as having only minor effect in the mechanical integrity, gunshot or holes should not represent a mechanical issue for composite either as these are of larger diameter and wall thickness than typical hollow core insulators. The resistance to vandalism is further supported by the fact that composite poles can be drilled to allow mounting of crossarms and insulators. A composite tower will however still buckled if subjected to severe impacts from very heavy equipment like cars and agricultural machines [57, 58, 60, 61].

5.3.6 Analysis of con's and pro's

In table 5.4 an overview of the advantages and disadvantages of composite based overhead lines compared to steel towers and wood poles are presented.

Table 5.4: Comparison of composite towers to steel towers and wood poles [53, 59].

	Composite towers	Steel towers	Wood poles
UV stability	Not an issue with protection	Not an issue	
Maximum heights	ca. 40 m (standard)	Fitted to project	Limited by tree height
Life expectancy	up to 80 years	50 years (can be prolonged with regalvanised)	
Earth wire	Non conductive, earth wire can run inside or outside	Conductive, structure used as downconductor	Non conductive, earth wire can run outside
Maintenance	None to very little		
Temperature range	± 50 °C	Higher than composite	
Bio stability	Inert	Inert	Susceptible to attack by birds, insects, fungus and rot
Weight	Light	Very heavy	Heavy
Impact resistance and deformation	High impact strength, no plastic deformation	Plastic deformation possible	
Mechanical aging	Time dependent		Slow reduction of mechanical strength will take place when exposed to the elements

Chapter 6

Dimensioning

Dimensioning of overhead lines consists of several disciplines which must be combined to ensure the electrical, mechanical and thermal demands are adhered to. In this chapter demands for clearances and how clearances are affected by overhead line voltage level and conductor sag due to electrical and mechanical loads will be presented. Besides clearance, how towers and insulators are affected by the mechanical loads and voltage levels will be shortly discussed.

6.1 Clearances and Insulation Coordination

The electrical dimensioning of overhead line systems revolves around ensuring that the system does not flashover due to the voltages on the phases and thereby have an acceptable performance or security of supply through insulation coordination but also – and more importantly – ensuring the safety of the public in the vicinity of overhead lines.

Ensuring the safety of the public in respect to operation of overhead line systems are done through the use of clearance – required "safety" distances from energised line components to grounded objects – specified by the authorities. Clearances are the main protection mean of protecting the public but also touch and step potential must be controlled to avoid risks to the public. Step and touch potential in contrast to clearances will not be treated.

Clearances are needed since the electrical field generated by overhead lines during normal operation and transients can results in flashover of air gaps and thus form a conductive path to objects to close to the line. However the distance from overhead lines to grounded objects is affected by the mechanical and electrical (current) loads on the system. These factors will be examined closer in section 6.2 below.

6.1.1 Clearances

Electrical clearances in overhead lines consist of both internal clearances – distances between conductors and grounded structures like towers and ground wires – and external clearance covering distances to element external to the system like building, vehicles, railways and people. Clearances that must be kept in overhead line systems exceeding AC 45 kV are defined in CENELEC standard EN50341-1 [99]. Before the publication of the European standard, Cigré published a report on tower top geometry (mainly on clearances under insulator swing due to wind covering the practise in several different countries [114].

The electrical clearances that must be kept is an important factor in overhead line design ensuring both an acceptable performance of the overhead line system as well as ensuring that it is safe to be near and in the case of live line working within the overhead line system. As such the clearance define the absolute minimum distances that must be kept in an overhead line tower top, in the span and from phases to the general public.

The clearances are based on some fundamental distances, which definitions are [42, 99]:

- D_{el} – The basic electrical clearance which is used to described the necessary clearance to prevent flashover – under fast front (lightning) and slow front (switching) transients – between live and grounded parts, where the earth parts can be both internal and external to the system. The clearance applies for phase to earth voltages and is indexed by sf for slow front or ff for fast front.
- D_{pp} – The basic clearance used to described the necessary distance to prevent phase-phase flashover under fast front (lightning) and slow front (switching) overvoltages. The clearance applies for phase-phase voltages and is indexed by sf for slow front or ff for fast front.
- D_{50Hz} – The 50 Hz or power frequency clearance describing the minimum clearance to avoid flashover under power frequency voltage. This clearance is usually only applied under severe climatic mechanical loads such as extreme wind causing the conductor to swing out. Here the clearance needed for power frequency is often used due to low probability of extreme wind and voltage transients happening at the same time. Indexed by either pe or pp for phase-to-earth and phase-to-phase respectively.

In table 6.1 some of the clearances demands from CENELEC EN50341-1 and the Danish Normative National Aspect (NNA) are presented. The clearances are define based on D_{pp}, D_{el}, $D_{50Hz-pp}$ and $D_{50Hz-pe}$ to make them applicable on all voltage levels. Besides the clearances demands being stated under different load situations – maximum design temperature, ice loads, wind loads and galloping – the clearances are also stated separately for at the tower and in the span.

For clearance to ground or crosses objects external to the system further clearance is added. This clearance is in [42] referred to D_{add} however it does not cover one specific value

Table 6.1: Minimum clearances within the span and at the tower defined in EN50341-1 and EN50341-3 DK NNA [99, 115].

Load cases	Within the span		At the tower		Remarks
	Phase conductor - phase conductor	Phase conductor - earth conductor	Between phases and/or circuits	Between phase conductors and earthed parts	
Maximum conductor temperature	D_{pp}	D_{el}	D_{pp}	D_{el}	Load conditions in still air
Ice load	D_{pp}	D_{el}	D_{pp}	D_{el}	Load conditions in still air
Wind load (except extreme wind load)	$k_1 \cdot D_{pp}$	$k_1 \cdot D_{el}$	$k_1 \cdot D_{pp}$	$k_1 \cdot D_{el}$	The reduction factor k_1 is defined in the NNAs
Extreme wind load	$D_{50Hz-pp}$	$D_{50Hz-pe}$	$D_{50Hz-pp}$	$D_{50Hz-pe}$	
Clearances in Danish NNA					
Maximum design temperature	D_{pp}	D_{el}	D_{pp}	D_{el}	Loads conditions in still air
Conductor swing	$0.7 \cdot D_{pp}$	$0.7 \cdot D_{el}$	$0.7 \cdot D_{pp}$	$0.7 \cdot D_{el}$	Because of small probability of simultaneous occurrence of an overvoltage whilst the conductor is moved by wind load, clearance may be reduced by 0.7
Galloping conductor	$D_{50Hz-pp}$	$D_{50Hz-pe}$	D_{50Hz_pp}	$D_{50Hz-pe}$	The over-all design shall ensure that these clearances in general are respected during galloping incidents

since the added clearance is dependent the type of the crosses object. In EN50341 part 1 and part 3 both general and national specific values are given for the added clearance. In table 6.2 several examples of clearances demands in EN50341 are presented. The standard should be consulted to get the full picture of the clearance demands [42, 99, 115].

6.1.1.1 Clearances and Composite Materials

As stated previously clearances are minimum required distances across air gaps need to ensure a satisfactory and safe operation of overhead lines. As the distances are all related to air, this being the primary insulation of overhead line systems, the clearances are not affected by the choice of materials for the overhead line system directly. The distances between live parts and live part and earthed part are still to be maintained. What the introduction of composite materials however may introduce into the overhead line system is changes in which parts of the system that are usually insulating and conductive.

A good example is the tower structure which is conventionally made of steel at EHV. If the steel tower is replaced by insulating composite materials, this may give rise to a change in the internal distances that must be kept due to clearance demands.

The primary contribution with regard to internal and external clearances that composite materials can contribute with is that for overhead line conductors with composite cores improved sag characteristics can be achieved. By reducing the sag of overhead line conductor clearances for conductor swing and galloping in the Danish NNA of EN50431 are reduced. Furthermore height of tower can be reduced since the required height is determined by arrangement and sag of conductors and demands for clearances. The internal clearances are also determined by the sag of conductors and clearances to grounded parts and between conductors. Therefore compared to ACSR conductors a reduction in the overall distances used in the tower top geometry may be possible. The sag of composite based overhead line conductors are examined in section 6.2.1.

6.1.2 Insulation Coordination

In the following the principles of insulation coordination are presented. Insulation coordination is here used to determined the electrical clearances in air D_{50Hz}, D_{el} and D_{pp} for an overhead line system as presented in section 6.1.1. A definition of insulation coordination, which will be used in the present work, is;

> "*Selection of the dielectric strength of equipment in relation to the operating voltages and overvoltages which can appear on the system for which the equipment is intended and taking into account the service environment and the characteristics of the available preventing and protective devices.*"
>
> IEC 60071 [116]

Table 6.2: Minimum clearances to remote areas, roads and railways as defined in EN50341-1 and EN50341-3 DK NNA [99, 115].

Load cases	Normal ground profile (remote areas)	Trees under the line		Road surface or top of rail (with electrification)	Electrical traction system of railways
		Climbable	Not climbable		
Maximum conductor temperature	$5m + D_{el}$	$1.5m + D_{el}$	D_{el}	$6m + D_{el}$	$2m + D_{el}$
Ice load	$5m + D_{el}$	$1.5m + D_{el}$	D_{el}	$6m + D_{el}$	$2m + D_{el}$
Wind load	$5m + D_{el}$	$1.5m + D_{el}$	D_{el}	$6m + D_{el}$	$2m + D_{el}$
Remarks	Basic requirement is that a vehicle or person can pass under the line without danger	Horizontal clearances of $1.5m + D_{el}$ and D_{el} for climbable and unclimbable respectively		Minor roads as defined in NNA can reduce clearance with 1 m	Also special load case with conductor swing
Clearances in Danish NNA					
Maximum design temperature	$5m + D_{el}$	$1.5m + D_{el}$	D_{el}	$6m + D_{el}$	$0.5m + D_{el}$
Conductor swing	$5m + D_{el}$	$1.5m + D_{el}$	D_{el}	$6m + D_{el}$	$0.5m + D_{el}$
Galloping conductor	Not specified	Not specified		$3m + p \cdot y_0 + D_{el}$	$p \cdot y_0 + D_{el}$
Remarks	Basic requirement is that a vehicle or person can pass without infringing D_{el}	Horizontal clearances of $1.5m + D_{el}$ and D_{el} for climbable and unclimbable respectively		Minor roads (no national route number) may reduce clearance by 1 m. Horizontal clearance of 10 m for MDT and CG, 2 m for CS.	

Or put very shortly, selection of the strength of the insulation.

There are two approaches to insulation coordination; the deterministic (referred to as "conventionally assumed" in IEC 60071) and the statistical. In the deterministic approach the maximum overvoltages occurring and the insulation strengths of the components of a system are all assumed to be at certain levels found either by design experience, service and test measurements or system simulations. In the statistical approach a comprehensive knowledge of the statistical distribution of overvoltages and insulation strengths are needed and based on these a risk of flashover can be calculated for the system insulation.

In equation form the two approaches can be described by the following set of equations.

$$U_{rp-max} < U_{W-min} \tag{6.1}$$

The maximum representative overvoltage, U_{rp-max}, must be less than the minimum withstand strength, U_{W-min}, of the insulation.

$$R = \int_0^\infty f\left(U\right) F\left(U_W\right) dU \tag{6.2}$$

The statistical risk of flashover, R, can be determined by integrating the product of the probability distribution function of a certain overvoltage in the system, $f\left(U\right)$, by the cumulative distribution function of insulation failure, $F\left(U_W\right)$.

The voltages and overvoltages that can be found in a high voltage systems are defined in insulation coordination standard IEC 60071-1 [116]. An overview is given in table 6.3.

In the insulation coordination standard is furthermore the standardised insulation levels. These insulation levels are also applicable to overhead lines and are therefore important to consider in the present work as these insulation levels will determined the clearances needed for an overhead line system.

The insulation levels are divided into two ranges; range I (1 kV $< U_m \leq$ 245 kV) and range II (245 kV $< U_m$). The reason for this division is that at 245 kV the dimensioning overvoltages goes from being temporary and lightning overvoltages to being switching and lightning overvoltages.

6.1.2.1 Power Frequency

The representative overvoltages under power frequency voltage are the peak voltages applied to the system by the sinusoidal AC voltage on the system. For phase to phase the representative overvoltage is the peak of the maximum system voltage while for the

Table 6.3: Voltages and overvoltages as defined in IEC 60071-1 [116].

Low frequency	Covering both basic power frequency voltage and temporary overvoltage that can arise in the system
Continuous	The power frequency voltage of the system being either 60 or 50 Hz
Temporary	Temporary overvoltages are voltages in the range of the power frequency. Temporary overvoltages are have a duration of one 50 Hz period up to an hour
Transients	Transients are overvoltages that have a duration shorter than one period of the power frequency voltage and can be several times larger in amplitude. Transients are often characterised by a front time and a time to half
Slow front	Slow front or switching overvoltages are primarily cause by switching elements in the system such as breakers. They can have front in the range of 0.1 μs to 5000 μs and a time to half $\leq$ 20 ms
Fast front	Fast front or lightning overvoltages are primarily caused by lighting strokes hitting overhead line conductor or ground wires. They can have a front of 0.1 μs to 20 μs with a time to half $\leq$ 300 μs
Very fast front	Are characterised by a front time $\leq$ 100 ns and frequencies between tens of kHz to hundreds of MHz

phase to earth the representative overvoltage is the peak of the maximum phase to earth voltage.

When considering insulation coordination for an overhead line several different situation or flashover paths needs to be considered as seen under the section on clearances (6.1.1). Besides flashover across the air insulation of the system in example under conductor swing to the tower or other phases, also the flashover of an insulator under contaminated condition needs to be considered. The performance of contaminated insulators is mainly dependent on power frequency voltage as the insulator can sustain relatively larger switching and lightning overvoltages without worsening of the performance of the insulator.

An insulator performance under contaminated conditions is very much dependent on insulator type and material. In IEC 60815 [84, 85, 86] the dimensioning and selection of insulators is standardised for glass, ceramic and polymer insulators. The main tool in the standard is the selection of creepage for insulators based on SPS (site pollution severity). The recommendations are given in table 6.7 as either USCD (unified specific creepage distance – based on phase to earth voltage) or SCD (specified creepage distance – based on phase-to-phase voltage).

It is here that composite insulators, especially those with silicone housing, have shown to have a superior performance to glass and ceramic insulators with the same creepage path. As previously stated in section 5.1.2.2, speculations into whether or not creepage distances for silicone insulators can be reduced have and is still a subject for discussion. However in [87] is it stated that for composite apparatus insulators the pollution class or SPS can be lowered one compared to IEC 60815 recommendations. Concerning line suspension or post insulators there have not be found similar suggestion to deviate from

Table 6.4: Standard insulation levels as defined in IEC 60071-1 for range I for selected voltage levels [116].

Highest voltage for equipment kV (rms)	Standard short-duration power frequency withstand voltage kV (rms)	Standard lightning impulse withstand voltage kV (peak)
145	(185) 230 275	(450) 550 650
170	(230) 275 325	(550) 650 750

Table 6.5: Standard insulation levels as defined in IEC 60071-1 for range II for selected voltage levels [116].

Highest voltage for equipment	Standard switching impulse withstand voltage			Standard lightning impulse withstand voltage
	Longitudinal insulation	Phase to earth	Phase to phase (ratio to the phase to earth peak value)	
kV (rms)	kV (peak)	kV (peak)		kV (peak)
420	850	850 1175	1.60	1050
	950	950 1300	1.50	1175
	950	1050 1425	1.50	1300

the IEC 60818 standard in the available literature at present.

The insulation strength of the direct insulation distance across an insulator – the direct distance in air from insulator top to bottom or non-polluted insulation distance – must be determined through type tests on insulators.

The clearances needed in air at 50 Hz can be found based on knowledge of the voltages in the system and through data presented in appendix E of [99].

The basic electrical clearance for power frequency voltage, $D_{50Hz,pe}$, can be calculated based on the representative overvoltage, $U_{rp} = U_s/\sqrt{3}$ which is equal to the highest phase-to-earth voltage (RMS). Further more correction factors for gap type, $K_g, pf = 1.35 \cdot K_g - 0.35 \cdot {K_g}^2$, for deviation from 50 % withstand voltage to the required design

Table 6.6: Representative overvoltages for power frequency voltage.

	U_{rp} phase to earth	U_{rp} phase to phase
Power frequency	$\frac{\sqrt{2} \cdot U_S}{\sqrt{3}}$	$\sqrt{2} \cdot U_S$

Table 6.7: Creepage distance dependent on site pollution severity (SPS) for polymer insulators [86].

SPS	USCD mm/kV$_{pe}$	SCD (old) mm/kV$_{pp}$
Very light	22	13
Light	28	16
Medium	35	21
Heavy	44	26
Very heavy	55	32

withstand voltage, $K_{z,pf} = 0.91$, and for altitude of the air insulation, K_a.

$$D_{50Hz,pe} = \left(\frac{e^{\frac{U_S}{750 \cdot \sqrt{3} \cdot K_a \cdot K_{z,pf} \cdot K_{g,pf}}} - 1}{0.55} \right)^{0.83} \tag{6.3}$$

The clearance for the 50 Hz system voltage, $D_{50Hz,pp}$, is calculated with the representative voltage as the highest system voltage, $U_{rp} = U_s$.

$$D_{50Hz,pp} = \left(\frac{e^{\frac{U_S}{750 \cdot K_a \cdot K_{z,pf} \cdot K_{g,pf}}} - 1}{0.55} \right)^{0.83} \tag{6.4}$$

6.1.2.2 Switching transients

Table 6.8: Representative overvoltages for switching voltage voltages.

	U_{rp} phase to earth	U_{rp} phase to phase
Switching	$K_{cs} \cdot U_{e2\%,sf}$	$1.4 \cdot K_{cs} \cdot U_{e2\%-sf}$

The basic electrical clearance for switching overvoltages, $D_{el,sf}$, can be calculated based on the representative overvoltage, $U_{rp} = K_{cs} \cdot U_{2\%,sf}$, which is equal to the 2 % switching withstand voltage, the voltage at which 2 % of the switching overvoltages will lead to a flashover, multiplied by a statistical coordination factor, K_{cs}. Further more correction factors for gap type, $K_g, sf = K_g$, for deviation from 50 % withstand voltage to the required design withstand voltage, K_z, and for altitude of the air insulation, K_a.

$$D_{el} = \frac{1}{0.46} \cdot \left(e^{\frac{K_{cs} \cdot U_{e2\%,sf}}{1080 \cdot K_a \cdot K_{z,sf} \cdot K_{g,sf}}} - 1 \right) \tag{6.5}$$

For the clearance for the phase-to-phase case, $D_{pp_{sf}}$, the representative overvoltage is multiplied by a factor of 1.4.

$$D_{pp} = \frac{1}{0.46} \cdot \left(e^{\frac{1.4 \cdot K_{cs} \cdot U_{e2\%,sf}}{1080 \cdot K_a \cdot K_{z,sf} \cdot K_{g,sf}}} - 1 \right) \tag{6.6}$$

6.1.2.3 Lightning transients

Table 6.9: Representative overvoltages for lightning voltages.

	U_{rp} phase to earth	U_{rp} phase to phase
Lightning	$U_{90\%,ff}$	$1.2 \cdot U_{90\%-ff}$

The basic electrical clearance for lightning overvoltages, $D_{el,ff}$, can be calculated based on the representative overvoltage, $U_{rp} = U_{90\%,ff}$, which is equal to the 90 % lightning withstand voltage, the voltage at which 10 % of the lightning overvoltages will lead to a flashover. Further more correction factors for gap type, $K_g, ff = 0.74 + 0.26 \cdot K_g$, for deviation from 50 % withstand voltage to the required design withstand voltage, K_z, and for altitude of the air insulation, K_a.

$$D_{el,ff} = \frac{U_{90\%,ff}}{530 \cdot K_a \cdot K_{z,ff} \cdot K_{g,ff}} \tag{6.7}$$

For the phase-to-phase case the lightning overvoltage clearance, $D_{pp,ff}$, is multiplies by a factor of 1.2.

$$D_{pp,ff} = \frac{1.2 \cdot U_{90\%,ff}}{530 \cdot K_a \cdot K_{z,ff} \cdot K_{g,ff}} \tag{6.8}$$

6.1.2.4 Gap factors

The gap factors used in the determination of clearance requirements are here presented for use in overhead lines. The gap factor is based on switching overvoltages, which is why $K_{g,sf} = K_g$

Table 6.10: Gap factors for overhead lines clearances (conductor-to-X) [42, 116].

Type of gap X	Slow front overvoltage $K_{g,sf} = K_g$	Fast front overvoltage $K_{g,ff}$	Power frequency voltage $K_{g,pf}$
Obstacle	1.30	1.08	1.16
Plane	1.15	1.04	1.09
Tower window	1.25	1.07	1.14
Tower	1.45	1.12	1.22
Conductor	1.60	1.16	1.26

6.2 Sag and loadability

Overhead line conductors will sag due the mechanical and electrical (heating) load on the conductors in service. The sag will change over time as the loads vary with changes in the current carried by the conductor or due to climatic loads occurring for a period of time.

In the following sections key characteristics of conductors containing composite materials under mechanical and electrical load will be investigated and compared to conventional steel-aluminium conductors.

6.2.1 Sag and Tension of Conductors

Overhead line conductors are carried by suspension or tension towers. Conductors will due to the long spans covered and the weight of the conductors sag up to several metres near the centre of the span. The sag of overhead line conductors will furthermore be affected by the current carried by the line and mechanical loads on the line due to e.g. ice load and/or wind loads. It is important to keep the sag of the conductor under control to ensure that electrical clearance requirements are meet so that the line can be operated without danger to the general public.

Overhead line conductors when hung from towers are under tension caused by the load of the conductor, temperature changes of the conductor materials, climatic loads and installed tension of the conductor. Controlling the tension of the overhead line conductors are important both with respect to limiting sag but also to ensure that the conductor will not be loaded beyond it mechanical failure limit.

In the following sections the theory behind sag-tension calculations will be presented in short. Calculations carried out for composite material based conductors will be presented and concerns and key differences to conventional conductors are discussed.

6.2.1.1 Sag of Conductors

The sagging curve of a conductor follows a catenary curve which's equation is well described.

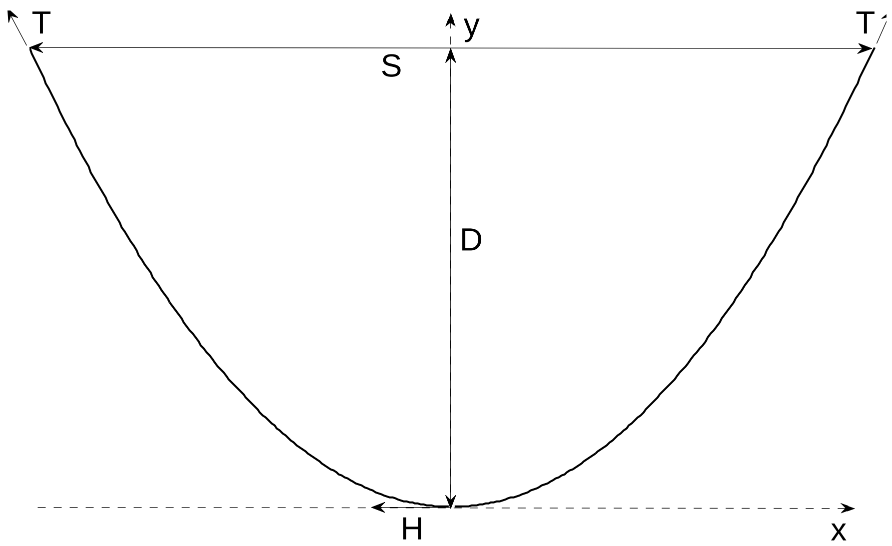


Figure 6.1: Sag curve for level spans [101].

The catenary equation describes the height, $y(x)$, above the vertex as a function of distance, x, to the vertex. Besides the distance to the vertex, $y(x)$ is depended on the horizontal tension in the line, H, and the weight of the line, w.

$$y(x) = \frac{H}{w}\left(\cosh\left(\frac{w \cdot x}{H}\right) - 1\right) \approx \frac{w \cdot x^2}{2 \cdot H} \tag{6.9}$$

The catenary curve can be approximated by a parabolic equation shown as the last term in equation (6.9). This corresponds to the first term of the Taylor development of the catenary equation and the parabolic expression is valid as long as $x^2w^2/12H^2 \ll 1$. The parabolic equation represents a relatively simple way of calculating the vertical displacement of the line in relation to its vertex.

For a level span the vertex is at $x = 0$ and the maximum vertical displacement in relation to the vertex at $x = \frac{1}{2}S$ where S is the span length, thus corresponding to half the value of the span. The maximal vertical distance from to vertex can for a level span be found at the support points.

The sag, D, of the conductor is the maximum distance from the conductor to the linear line passing through the support points of conductor. For a conductor in a level span the sag of the conductor corresponds to $y = \left(\frac{1}{2}S\right)$, e.g. the distance from a support point to the vertex of the catenary curve, as given in equation (6.10).

$$D = \frac{H}{w}\left(\cosh\left(\frac{w \cdot S}{2 \cdot H}\right) - 1\right) \approx \frac{w \cdot S^2}{8 \cdot H} \tag{6.10}$$

From (6.10) it can be seen that the sag of the conductor will decrease if the weight is reduce or the tension increased and reverse for increases in the sag. Furthermore for smaller spans the sag will be less than for larger spans. Therefore to reduce sag it would be prudent to decrease the weight of the conductor, increase the tension level and use small spans [38, 42**?**].

Since only level spans will be examined here, how to calculate sags in uneven spans – span with attachment points at different – will not be presented. However guidelines can be found in [101] and [42].

Length of Conductors

Another interesting parameter of conductors in tension spans is the length of the conductor. The conductor length, $L(x)$, in relation to the vertex of the catenary curve can be calculated from equation (6.11). The length of the conductor is, like the sag, dependent on the horizontal tension in the conductor, H, the weight of the conductor, w, and the distance to the vertex, x.

$$L(x) = \frac{H}{w}\sinh\left(\frac{w \cdot x}{H}\right) \approx x \cdot \left(1 + \frac{x^2 \cdot w^2}{6 \cdot H^2}\right) \tag{6.11}$$

The last term of equation (6.11) is a parabolic approximation as also noted for the sag in equation (6.9).

The full length, L, of a conductor in a level span can be calculated by use of equation (6.11) by multiplying the length of the conductor from the vertex to a suspension point $(L\left(\frac{1}{2}S\right))$ and multiplying by two. This applies since the span is level and thus the vertex corresponds to half the span or length of the conductor. Thus the length, L, of the conductor can be calculated by the horizontal tension, H, the weight of the conductor, w, and the span length, S.

$$L = 2 \cdot L\left(\frac{1}{2}S\right) = \frac{2 \cdot H}{w}\sinh\left(\frac{w \cdot S}{2 \cdot H}\right) \approx S \cdot \left(1 + \frac{S^2 \cdot w^2}{24 \cdot H^2}\right) \tag{6.12}$$

The conductor length can also be related to the conductor sag by the parabolic approximations as given in equation (6.13).

$$L \approx S + \frac{8 \cdot D^2}{3 \cdot S} \tag{6.13}$$

Transforming equation (6.13) gives the sag, D, as a function of the conductor length, L, as given in equation (6.14).

$$D \approx S \cdot \sqrt{\frac{3}{8} \cdot \left(\frac{L}{S} - 1\right)} \tag{6.14}$$

From equation (6.14) it can be seen that the sag of an overhead line conductor is dependent upon the length of the conductor. Thus a longer conductor will have larger sag than a shorter conductor all as being equal. This is important to keep in mind as the conductor's length is not only dependent on the mechanical load and resulting elastic elongation of the conductor but also on thermal and plastic elongation of the conductor [38, 42, 101]. This will be examined further in section 6.2.1.2.

Conductors in Tension Spans

The sag of a conductor in a span is dependent upon the weight of the conductor, the span length and the tension in the conductor. The span length is constant and will not change or cause a change in sag. The weight can change due to climatic loads such as wind or ice load and will increase the sag if these loads occur in the span. The tension of the line however is influenced both by the loading of the line but also by adjacent spans.

The tension of the line will change with the conductor length as will be shown in the section on elongation of conductors in section 6.2.1.2. Furthermore since a span is seldom mechanically isolated from adjacent spans (unless both towers are tension towers) the tension will also be influences by climatic loads in other spans. Normally however, without local climatic loads, the tension will equalise in span of the same tension section since the bottom of suspension insulator are free to move and will do so which result in approximate equalisation of the tension in adjacent spans [38, 42, 101].

On overhead lines three kinds of towers are normally used. These are suspension towers, angle towers and tension towers. In suspension towers overhead line conductors normally only transfer a vertical load to the tower since the conductors are suspended from the tower structure. Suspension towers can also be used for small angles where only a small amount of tension load is transferred to the tower. For larger angle changes in the routing of the line angle towers must be used. Here both horizontal and vertical loads are transferred to the tower. The tower will still however not receive the full suspension load in the conductor. For very large angels and tension section ends, dead-end towers or tension towers are used. These towers experience the full tension in the overhead line conductors and therefore must be more mechanically robust than suspension and angle towers since they experience a greater load.

Ruling Span

A good approximation of the sag of a conductor in different spans in the same tension section of a line can easily be calculated by used of the Ruling Span method. The method will however not be presented here, instead [42], [38] or [101] can be recommended for information on the ruling span method.

Common Tension Levels Used in EHV AC Systems

There are great differences in the tension levels used for EHV AC systems internationally and can also be nationally. How they are specified can further vary being either as allowable stress (force per cross section) or percent rated tensile strength (RTS) or rated breaking strength (RBS).

Allowable tension levels in overhead line conductors are not directly specified in the European standard for overhead electrical lines above 45 kV [99]. Similar the national normative aspects of the standard do not mention tension limits either [115].

In Cigré Brochure 324 [101] guidelines on conductor tensioning is now mentioned. Generally three situations needs to be considered; initial tension, tension after high loading (defined as final) and tension under high loads (ice and/or wind loads). The recommendations are based on percent RTS and are as specified in table 6.11.

Table 6.11: Conductor tension level recommendation in Cigré Brochure 324 [101].

Load type	RTS limit
Initially installed tension – without ice or wind load at 15 °C	20 to 30 %
Final tension – tension after heavy loads and without wind or ice at 15 °C	15 to 25 %
Maximum tension under heavy climatic loads – ice and/or wind loads	50 to 75 %

The reason for the maximum tensile load being limited to 75 % is to avoid tensile failures of conductors in service due to ageing and deterioration of the conductor's tensile strength through its life time. Furthermore the heaviest loads on overhead line conductors are usually climatic in nature and thus vary with the line geographical location. Climatic loads used in Europe are described in EN50341-3 [115].

At Energinet.dk, the Danish TSO (transmission system operator), the following values are standardised for conductors on transmission level; 55 kN/mm^2 and 65 kN/mm^2. Which values that should be used are dependent on whether or not vibration dampers are applied in on the line, thus 55 kN/mm^2 is used if the line is not fitted with vibration dampers and 65 kN/mm^2 with vibration dampers. Normally vibration dampers are used and thus 65 kN/mm^2 have been standard on many Danish overhead lines. How vibration and tension in a line are connected will be examined further in section 6.2.2.2.

6.2.1.2 Conductor Elongation

In section 6.2.1.1 the connection between conductor sag, length and tension was presented. The length of a conductor is however not a constant over the conductor in-service and loading history. In equation (6.12) it was shown, that the conductor length will change as a function of horizontal tension, H, in the conductor.

A conductor will be installed at certain temperature and tension in a span of a certain length. At the installed conditions the length of the conductor can be calculated based on the previously presented equation (6.12). The length of the conductor will however change through its service life due to temperature changes in respect to the installed temperature (thermal elongation), mechanical load caused by ice and/or wind loads on the conductor (elastic and plastic elongation) and due to metallurgical creep or settling of the conductor (plastic elongation). Most of the elongation of overhead line conductors will take place as elastic elongation and the conductor will thus elongate with increase temperature and mechanical load and shorten with decreases in temperature and mechanical load. These mechanism are all depicted in figure 6.2.

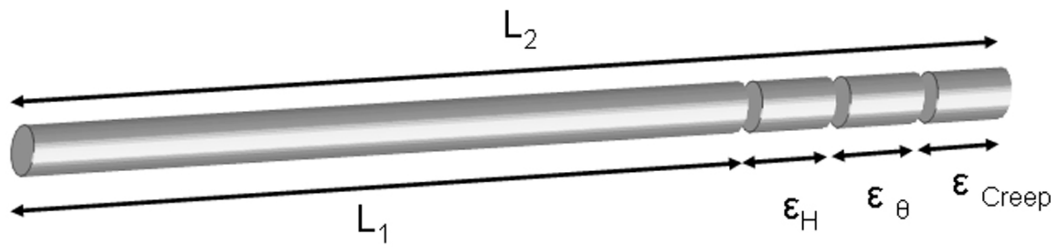


Figure 6.2: Conductor elongation components

The length of a conductor with elongation, L_2, can calculated based on the original installed length, L_1, of the conductor and the different types of elongation; elastic elongation ε_H, thermal elongation ε_θ and creep elongation ε_{Creep}.

$$L_2 = L_1 \cdot (1 + \varepsilon_H + \varepsilon_\theta + \varepsilon_{Creep}) \tag{6.15}$$

The different conductor elongation causes, being either plastic or elastic in nature, are shortly described in the following sections.

Elastic Elongation due to Mechanical Loading

When a conductor is loaded mechanically by a tensile load greater or smaller than the load when the conductor was installed, the length of the conductor will change from the first state, L_1, to the second state, L_2. The length of the conductor after the change in the horizontal tension is dependent on the original horizontal tension in the conductor, H_1, the new horizontal tension, H_2, the elastic modulus, E, of the conductor and the cross section, A, of the conductor.

$$L_2 = L_1 \cdot \left(1 + \frac{H_2 - H_1}{E \cdot A}\right) \tag{6.16}$$

For conductor consisting of more than one material, the total horizontal in the conductor, H_{AC}, equals the sum of the horizontal tensions in the aluminium conductor layer, H_A, and the core, H_C.

$$H_{AC} = H_A + H_C \tag{6.17}$$

The horizontal tension in the parts of an overhead line conductor can also be calculated based on the total horizontal tension in the conductor. For the aluminium outer layers, the tension, can be calculated based on the total horizontal tension of the conductor, H_{AC}, the elastic modulus of the conductor and the aluminium, E_{AC} and E_A respectively, and the cross sections of the total conductor and the aluminium part, A_{AC} and A_A respectively.

$$H_A = H_{AC} \cdot \frac{E_A \cdot A_A}{E_{AC} \cdot A_{AC}} \tag{6.18}$$

Likewise for the horizontal tension in the core of the conductor, except the cross section and the elastic modulus of the aluminium in equation (6.18) is replaced by the core characteristics, A_C and E_C respectively.

$$H_C = H_{AC} \cdot \frac{E_C \cdot A_C}{E_{AC}} \tag{6.19}$$

The elastic elongation, ε, of the conductor due to tension is calculated from the horizontal tension, H, and the cross section of the conductor, A.

$$\sigma = \frac{H}{A} \tag{6.20}$$

The elongation change, $\Delta\varepsilon$, in a conductor is instead of the total horizontal tension in the conductor based on the change in horizontal tension, ΔH.

$$\Delta\sigma = \frac{\Delta H}{A} \tag{6.21}$$

For a conductor it applies that the elongation of the total conductor, ε_{AC}, is equal to the elongation of the aluminium, ε_A, which is again equal to the elongation of the core, ε_C. This applies because the conductor parts are clamped together at the ends of the tension spans. Therefore the length of the conductor core, the aluminium layers and the conductor as a whole must be of the same length and thus also the elongation of the core, the aluminium and the conductor as a whole. This is expressed in equation (6.22).

$$\varepsilon_{AC} = \varepsilon_A = \varepsilon_C \tag{6.22}$$

Plastic Elongation

Plastic elongation of conductor happens primarily due to two factors. These are high mechanical loads on the conductor and creep of the conductor materials.

Plastic Elongation due to High Loading

Plastic elongation of conductors can be observed when the conductors are loaded with a high long and afterwards unloaded again. An increase in the final unloaded length of the conductor compared to the initial unloaded length can be observed. For conventional conductor the creep elongation due to high loads is primarily caused by the aluminium in the conductor since the core will only have a very small plastic elongation.

The creep elongation, $\varepsilon_{Creep,A}$, of aluminium 37-strand A1 is well known and is described by the following equation [101].

$$\varepsilon_{Creep,A} = 0.01698 \cdot \sigma_{max} \tag{6.23}$$

The creep elongation is dependent on the maximum loading or stress experienced by the conductor, σ_{max}, in its life time and not the actual stress or load corresponding to the load situation examined.

To illustrate creep elongation of conductors due to high loading the stress-strain curve for a 795 kcmil ACCR conductor is included in figure 6.3.

From figure 6.3 it can be seen that the stress-strain curves for the aluminium, the core and for the total conductor are different for loading and unloading resulting in increase in

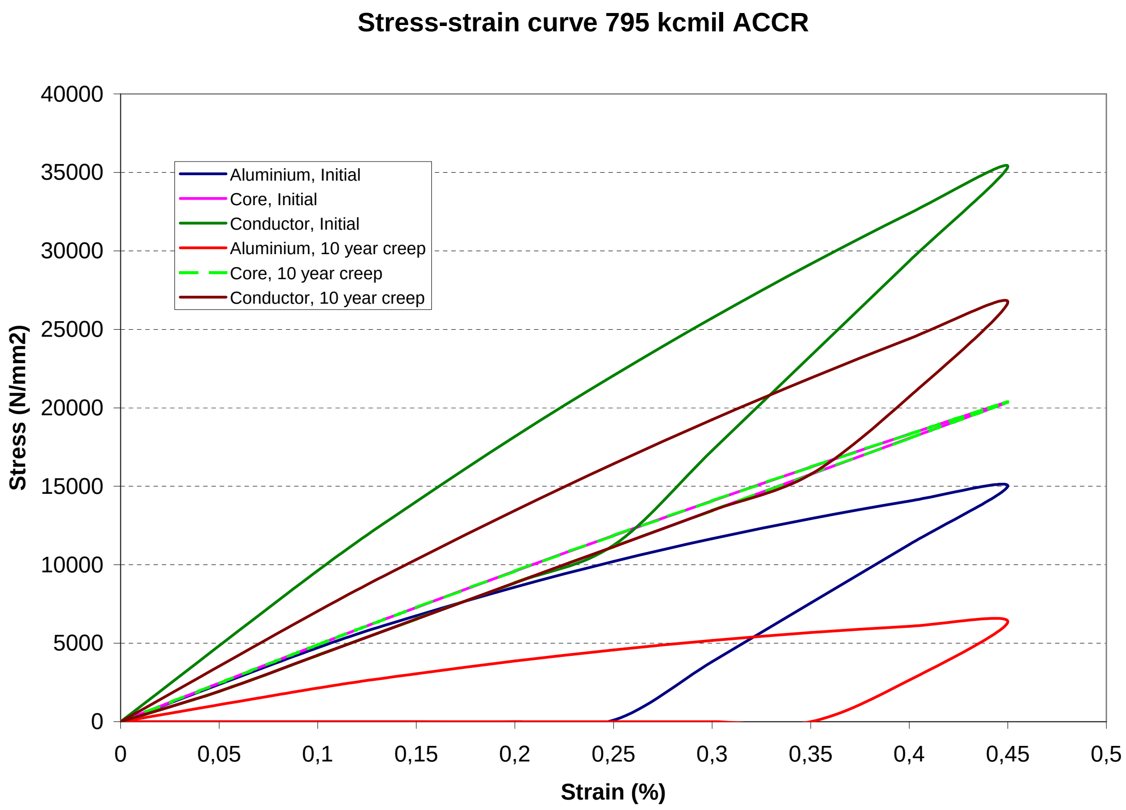


Figure 6.3: Stress-strain curves for a 795 kcmil (400 mm^2) ACCR conductor [47].

the unloaded elongation. This is most pronounced for the aluminium layers. Only small changes can be observed for the 3M composite core.

Plastic Elongation over Time

Traditionally creep of conductors over time independent of loading has been metallurgical creep since both core and the outer conductive layers are metals in ACSR conductors.

The metallurgical creep for A1 is well known and is described in its final state by the equation below [101]. The creep over time or metallurgical creep, $\varepsilon_{Creep,A}$, in this case aluminium, is dependent on the stress, σ in MPa, and the time, t, in hours.

$$\varepsilon_{Creep,A} = 1.23 \cdot \sigma^{1.3} \cdot t^{0.16} \tag{6.24}$$

For the steel cores of conductors very little metallurgical creep can be observed and it is usually neglected. For composite cores plastic elongation over time is close to non-existing and according to the manufacturer's data for both ACCC and ACCR conductors neither will experience creep over time. This can be observed for a 10 year period for the ACCR conductor in figure 6.3.

Thermal Elongation

The thermal elongation of conductors occurs when the temperature of the conductor increases beyond the temperature at installation. Likewise the conductor will contract if cooled below the installation temperature.

The thermal elongation of a conductor is proportional with the temperature difference, $\Delta\theta$, between the actual temperature of the conductor and the temperature of the conductor at installation. The coefficient multiplied with the temperature difference is known as the thermal expansion coefficient, α, and is dependent on material.

$$\frac{\Delta L}{L} = \alpha \cdot \Delta\theta \tag{6.25}$$

The thermal coefficient of a conductor, α_{AC}, consisting of multiple materials is calculated as described in equation (6.26). Here the thermal expansion coefficients of the aluminium and core, α_A and α_C respectively, together with the materials ratio of elastic modulus, E_A and E_C respectively, and cross section, A_A and A_C respectively, to the conductor's, E_{AC} and A_{AC}, are used [101].

$$\alpha_{AC} = \alpha_A \left(\frac{E_A}{E_{AC}}\right)\left(\frac{A_A}{A_{AC}}\right) + \alpha_C \left(\frac{E_C}{E_{AC}}\right)\left(\frac{A_C}{A_{AC}}\right) \tag{6.26}$$

6.2.1.3 Sag-Tension Calculations

The above sections 6.2.1.1 and 6.2.1.2 need to be combined to make a full sag-tension model for an overhead line conductor.

Several different sag-tension models exists and are in general listed in Cigré Brochure 324 [101]. These are in short listed in table 6.12.

Several different variants of the models in table 6.12 exists. One of the most used models is the "strain-summation method" [117, 118]. In the present work the variant "STOC" (strain tension in overhead conductors) is used as it is easy to implement. This variant is based on the experimental plastic elongation model. The "STOC" method is described in appendix A.

Table 6.12: Conductor elongation models [101].

Model name	Description
Linear elastic	Overhead conductors are modelled as linear springs with a single elastic modulus and a single thermal elongation thermal elongation coefficient.
Simplified plastic elongation	Conductors are modelled as linear springs and plastic elongation is calculated and added as a permanent change in length. Elastic modulus and thermal elongation is specified both for the aluminium layer and the core and a typical knee-point for tension shift to the core from the entire conductor can be calculated. The knee-point can however not be calculated as being dependent on conductor type, design load and span length.
Experimental plastic elongation	Overhead conductors are modelled as non-linear springs that elongates elastically as a function of tension and plastically as a function of tension and time and thermally as a function of temperature. For non-homogenous conductors the elongation is calculated separately for each component. Plastic elongation for “settling”, “creep elongation” and “permanent elongation loads due to high tension loads” are calculated based on an assumed life time loading events.

6.2.2 Load Cases for Sag-Tension Calculations and Tension Limits

The mechanical load on overhead line conductors will not stay constant through the life time of the conductor. Furthermore the mechanical load on overhead line conductors will also change the sag of the conductors as added weight of the conductor will result in greater sags as observed in section 6.2.1.1.

The two main concerns with respect to mechanical loading on overhead lines are loads to wind blowing across line and ice forming on the conductor thereby increasing the weight of the conductor and thereby the sag.

To avoid excessive sags the tension of the conductor can be increased. However this also increases the loads on tension structures and also increases the risk of Aeolian vibration.

In the following the standard load cases used for ice and wind load for overhead line conductors will be presented as will guidelines for tension limits. The consequences of these loads to the sag of composite based conductors are analysed and presented.

6.2.2.1 Ice and Wind Loads

Mechanical loads on conductors that can affect the sag of overhead line conductors are usually limited to wind and ice loads – so called climatic loads – that can be dependent on the time of year.

These loads are more or less independent on the conductor type though experiments with conductor surface coatings limiting the affect of climatic loads have been carried out. These loads must therefore also be examined for how they affect the sag and tension relationship of composite based conductors.

Both wind and ice loads are standardised in EN 50341 [99, 115]. For applications in Denmark, ice and wind load are only interesting with regard to mechanical loading of overhead lines and creep consideration for conductor sag under maximum temperature. Wind loads are not used directly when considering conductor swing nor are ice loads considered when calculating conductor sag as only galloping and maximum temperature sag is considered.

Ice Loads

Ice loads are not standardised in EN 50341-1 [99]. This is due to the ice load being very dependent on local climatic conditions.

In 50341-3 in the Danish NNA the characteristics ice load is set to be dependent on diameter, d, of the conductor. The characteristic ice load is based on a 30 mm conductor and reflects a 50 years return period (50 years will pass between the maximum loads corresponding to the characteristic ice load). The ice load, I_K, can be calculated from the following equation [115].

$$I_K = 12 + 0.9 \cdot d \tag{6.27}$$

The diameter, d, is entered in mm and the result, I_K, is in N/m. The characteristic ice load is added to the weight of the conductor and the entire span is assumed to be covered by ice for evaluation of the tension in conductors due to ice loads.

Wind Loads

As the calculation of wind loads are not directly used in the present work, the equations for calculation of the wind force are presented. For information on wind load calculations, consult [99].

The following should though be noted. The wind force on a conductor is dependent on the wind speed squared as well the height above ground (increases with height). In Denmark reference wind speeds between 24 m/s and 27 m/s are used for the characteristic wind speed. This is also increased with the height above ground of the conductor.

Wind loads are only used to determine the forces on conductors, insulators and towers for mechanical purposes and are not directly used when determining the electrical clearances in the Danish NNA of EN50341. Instead the conductor swing is described by simple expressions as described below [99, 115].

Conductor Swing

Conductor swing for clearance calculations are defined for two different positions in the Danish NNA of EN50341. These are at the tower and in the span.

At the tower the conductor swing will be limited to a radii of the insulator. The insulator is assumed to have a maximum swing of 45 °. This only applies for a suspension insulator. For V-sting insulator, line post and braced line post the insulator swing is set to zero and thus the conductor is fixed at the tower.

In the span the conductor swing, $CS(x)$, is described by the conductor sag at 0 °C, y_0, at point x and the connection length of the insulators, l_k. If the insulators are V-sting, line post or braced line post insulators the length of l_k is set to zero. As the weight of the conductors will affect the conductor swing, the conductor weight factor, k, is used in equation (6.28). The value of k is set to 0.7 for copper and steel conductors and to 0.85 for all other conductors. This represents that steel and copper conductors are generally heavier than "all other conductors" resulting in reduced conductor swing [115].

$$CS(x) = k \cdot (y_0 + l_k) \tag{6.28}$$

Combined Wind and Ice Load

Combined wind and ice loads can also be applying in the dimension of overhead lines. In the Danish NNA of EN50341 combined wind and ice load is limited to full ice load with a 40 & wind load. The reverse case with full wind and a reduced ice load is not used in the Danish NNA [99, 115].

Summery of Loads

In table 6.13 an overview of conductor loads determination of conductor tensions are given.

6.2.2.2 Aeolian Vibrations

Aeolian vibration can arise on overhead lines due to wind travelling across the conductors. The wind forces causes vertical motion of the conductor – Aeolian vibrations – with a

Table 6.13: Conductor tension load cases in EN 50341 and Danish NNA [99, 115].

Load case	Temperature (°C)	Load
Normal	-5	Conductor self-weight + normal additional load (respective increased additional load)
Normal	-20	Conductor self-weight
Normal	+15	Conductor self-weight + maximum wind load
Normal	+40	Conductor self weight
	Danish NNA	
Normal	-0	Conductor self-weight + combined ice and wind load
Normal	-20	Conductor self-weight
Normal	+5	Conductor self-weight + extreme wind

relatively short wave length and frequencies between 5 and 100 Hz. The amplitude is of the vibrations are relatively small. Aeolian vibrations can occur at winds having a laminar structure with velocities up to 10 m/s dependent on the terrain [42].

Aeolian vibrations on overhead conductors can lead to reduction in the total strength of the conductor due to fatigue and eventually conductor breakage. It is not uncommon that Aeolian vibrations can lead to breakage of individual aluminium strands on conductors. For conductors where the aluminium carries a part of the mechanical load this is also a reduction in total strength. Conductors where the aluminium strands do not carry a part of the mechanical load, breakage of the aluminium strands will not lead to a reduction in strength. Breakage of aluminium strands may increase the likelihood of corona activity at the conductor surface at the breakage point.

Leads to bending activity at the line ends which is the primary point of weakening.

To avoid Aeolian vibrations on overhead lines limitation to tension of the conductor when initially installed have often been used. This is reflected in the tension values of 15-25 % RTS for initial installation of overhead line conductors (see section (6.2.1.1)). The tension limit is meant to limit the EDS (everyday stress) on the line and thereby also Aeolian vibration by ensuring some self damping ability of the conductor. To help increase the Aeolian vibration damping ability dampers can be applied to line. This also in many cases makes it possible to increase the tension on the line. This is also reflected in the stress (tension per cross section) limits of the Danish TSO being 55 kN/mm^2 and 65 kN/mm^2 for conductors without and with dampers, respectively.

In Cigré Brochure 273 [104] the ratio H/w (tension over conductor weight) is used instead of horizontal tension to try and limit Aeolian vibrations. The H/w is further more made dependent on a description of the terrain in which the overhead line is situated. For damped conductors the relation LD/m (conductor length multiplied by conductor diameter over conductor mass) is further more used to determined the recommended tension levels with respect to Aeolian vibration. The tension level guidelines for everyday tension at the average temperature of the coldest month of the year are reproduced in table 6.14 and table 6.15.

Table 6.14: Recommended conductor safe design tension at the average temperature of the coldest month as a function of terrain category to avoid damage due to Aeolian vibration during the conductor's life time [104].

Terrain category	Terrain characteristics	H/w (m)
1	Open, flat, no trees, no obstructions, with snow cover, or near/across large bodies of water; flat desert.	<1000
2	Open, flat, no obstruction, no snow; e.g. farmland without any obstruction, summer time.	<1125
3	Open, flat, or undulating with very few obstacles, e.g. open grass or farmland with few trees, hedgerows and other barriers; prairie, tundra.	<1225
4	Built-up with some trees and buildings, e.g. residential suburbs; small towns; woodlands and shrubs. Small fields with bushes, trees and hedges.	<1425

The guidelines for tension levels are specified in the brochure as being applicable to AAC, AAAC, ACAR and ACSR conductors as they are based on operation experience with these conductors. The guidelines are not verified by the Cigré working group as being applicable to ACCC or ACCR conductors due to lack of information. The manufacturers of the ACCC and ACCR conductors have however carried out a number of test and it is recommended that the practise used for ACSR conductors is followed [46, 96].

Aeolian vibrations and composite material based conductors

From table 6.15 it can be seen that for single conductor span the maximum advisable horizontal tension is only dependent upon the conductor weight. Thus the maximum tension is independent of diameter and span length. In general this means as can be seen from the figure above that lighter conductors are should be tensioned at a lower limit than heavier conductors. For ACCC and ACCR conductors which are generally lighter compared to ACSR conductor of the same diameter this results in lower tensioning limits.

Lower tensioning limits for ACCC and ACCR conductors can have an affect on the sag of the installed lines and should thus be considered when calculating line sag. From table 6.15 and the figures above it can be seen that for the configuration of the conductor will have a great affect on advisable tension limits.

It should be noted that there are presently no reports on damages due to Aeolian vibration on ACCC or ACCR conductors however this is surely also related to the low number of conductors installed.

Table 6.15: Recommended conductor safe design tension at the average temperature of the coldest month as a function of terrain category to avoid damage due to Aeolian vibration during the conductor's life time – expanded [104].

Conductor configuration	Terrain category	H/w (m)	LD/m (m^3/kg)
Undamped single conductor (same as table 6.14)	1	<1000	–
	2	<1125	–
	3	<1225	–
	4	<1425	–
Single conductor with span-end Stockbridge dampers	1	$<2615/(LD/m)^{0.12}$	<15
	2	$<2780/(LD/m)^{0.12}$	<15
	3	$<2860/(LD/m)^{0.12}$	<15
	4	$<3030/(LD/m)^{0.12}$	<15
Twin horizontal bundled conductors with non-damping spacers and span-end Stockbridge dampers	1	$<2615/(LD/m)^{0.12}$	<15
	2	$<2780/(LD/m)^{0.12}$	<15
	3	$<2860/(LD/m)^{0.12}$	<13
		<2100	>13; <15
	4	$<3030/(LD/m)^{0.12}$	<6
		<2450	>6; <15
Triple apex-down bundled conductors with non-damping spacers and span-end Stockbridge dampers	1	$<2615/(LD/m)^{0.12}$	<15
	2	$<2780/(LD/m)^{0.12}$	<10
		<2100	>10; <15
	3	$<2860/(LD/m)^{0.12}$	<7
		<2275	>7; <15
	4	$<3030/(LD/m)^{0.12}$	<5
		<2500	>5; <15

Test on the Aeolian damage resistance of both ACCC and ACCR conductors have carried out by the manufacturers. For the ACCR conductor the test on Aeolian damage resistance showed no signs of damage or wear to the conductor [119, 120]. For the ACCC conductor however several strands of the aluminium were broken in the test. No damage or wear were however reported for the core and thus the mechanical integrity of the conductor as a whole should be maintained. This was confirmed by test of on the rated tensile strength of the conductor after the Aeolian vibration test [106].

Since no officials standards for testing of overhead line conductors with regard to Aeolian vibration damage resistance the IEEE standard 1138-1994 for OPGW's and Aeolian vibrations testing have been used in the referenced tests [106, 119, 120].

6.2.2.3 Galloping

Galloping of overhead line conductors are conductor oscillation that can take place on iced conductors. Ice accretion on conductor develops and unsymmetrical profile of the conductor which equals an aerodynamic unstable profile. Transverse wind force on the conductor develops oscillating motion of the conductor with amplitude as big as the sag of the conductor (several metres). Galloping can take place at wind velocities in the range from 6 to 25 m/s below 0 °C. The arising oscillation has a very low frequency being less than 1 Hz [42].

Normally conductor galloping is primarily a concern with regard to maintaining the internal electrical clearances between phases. However surface damages in the form of burns due to arcing and mechanical damage to the aluminium layers have been reported. In very rare cases galloping have let to line collapses – mechanical failure of supports [121]. Furthermore as with Aeolian vibrations, there is concern regarding bending loads at the suspension clamps and dead ends which could result in breakage of the strands in the conductor.

Several different means of avoiding or lessening galloping on overhead line conductors have been developed and are in use. These include inter-phase spacers, airflow spoilers and twisted conductors (two conductors are twister together giving a continuous change in shape of the cross section disturbing the air flow around the conductor) [121].

Galloping and composite conductors

As galloping is connected to the symmetry of a conductor, conductors based on composite materials are most like neither more or less prone to galloping. It is however not possible to predict this and in-service experience with composite based conductors and galloping have not been reported in the available literature.

For both the ACCC and ACCR conductors tests based on IEEE std. 1138-1994 (intended for OPGW conductors) have been carried out as for Aeolian vibrations. For both conductors armour rod suspension grips are used for suspension units. Both the ACCC and ACCR have been tested at 100,000 cycles with an amplitude of approximately 1 m in special setup. Neither conductor showed any signs of wear nor damage, thus their mechanical performance under galloping should be adequate [119, 122].

6.2.3 Thermal Loadability - Composite Based Conductors

To transport power, overhead lines need to be at a voltage potential and carry a current. The potential on the lines requires that the overhead line have sufficient insulation from the surrounding as not to flashover and interrupt power transfer. However dependent on the current carried on the line it will be heated due to ohmic losses (also called joule heating) in the line. The heating of an overhead line conductor can result in relatively large changes in the sag of the conductor due to thermal elongation as presented in section 6.2.1.2.

Besides heating of the current due to the current carried by the conductor ($Q_\Omega = I^2 R_{AC}$), the conductor will also be heated due to heating by the sun, Q_S. However cooling of the conductor will also take place through convection around the conductor, Q_C, and radiation of heat from the conductors to the surroundings, Q_R. Depending on the situation heat can also be stored in the conductor. Storing of heat in the conductor is a function of the temperature change over time and the heat capacity of the conductor, $m \cdot C\frac{d\theta}{dt}$. The energy balance of an overhead line is thus expressed by equation (6.29) [42, 100, 102].

$$Q_S + I^2 R_{AC} = m \cdot C\frac{d\theta}{dt} + Q_C + Q_R \tag{6.29}$$

The energy balance in equation (6.29) is approximate since magnetic heating, corona heating and evaporative cooling is neglected. However these three terms contributes very little to conditions under which the energy balance is normally applied and neglecting the terms is therefore fully valid [102].

In the following sections, the application of the energy balance presented above to determine the thermal loadability of an overhead line conductor under different situations will be presented in short. These situation covers the evaluation of the allowable current with respect to maximum sag, emergency loading of the conductor in a 15 min period and the temperature rise during fault currents on the line. For a thorough explanation [100, 102] should be consulted, these are IEEE and Cigré's guidelines, respectively.

6.2.3.1 Normal Operation – Thermal Rating

To ensure that overhead line conductors do not sag beyond the clearance limit to grounded objects it is important to determine the maximum temperature of the conductor at its designed maximum current loading – also called maximum design temperature (MDT) – at which the largest sag of a conductor due to temperature is achieved.

When the conductor is operating under normal operation it has reached equilibrium between heating and cooling of the conductor. The conductor is operating in a steady state and thus heat storage in the conductor will not take place. This reduces the energy balance to the following.

$$Q_S + I^2 R_{AC} = Q_C + Q_R \tag{6.30}$$

This can be rearranged to the following expression for the current, I, in the conductor as function of convective cooling, Q_C, radiation cooling, Q_R, solar heating, Q_S, and the resistance of the conductor, R_{AC}.

$$I = \sqrt{\frac{Q_C + Q_R - Q_S}{R_{AC}}} \tag{6.31}$$

Thus the current rating of an overhead line conductor can be carried out, if the heating, cooling and resistance parameters are known or estimated with a conservative estimation.

Determination of the cooling and heating parameters taking place around the conductor is dependent on several different factors. Here they are described in short [42, 100, 102].

Resistivity

The resistivity of a conductor is dependent on the conductor temperature. This is important to consider when calculating the thermal rating of an overhead line. The resistivity of a conductor must be calculated dependent on the frequency of the system. Thus the 50 Hz AC resistivity is required to calculate the thermal rating of and AC overhead line in Europe. The resistivity is assumed linear which is an approximation which serves its purpose satisfactory. The linearisation is based on two resistivity values at different temperatures which is often included with the data sheet for a conductor [42, 100, 102].

Solar Heating

Solar radiation will heat up an overhead line conductor and is dependent on the diameter of conductor, the absorptivity of the conductor, the intensity of the sun radiation and the height of sun over the horizon. The solar radiation is constant for a conductor and will thus be independent of the conductor temperature unlike the other heating and cooling parameters. At high temperature the solar heating will contribute relatively little to the energy balance of the conductor [42, 100, 102].

Convective Cooling

The convective cooling of an overhead line conductor can either take place as natural or forced convection. Natural convective cooling arises due to the temperature difference between the conductor and the surroundings. An updraft will be created around the conductor due to heating of the air surrounding the conductor thereby aiding in the cooling of the conductor. More predominant is however forced convective cooling of the conductor. Due to the air movement created by winds across the conductor heat will also be transferred away from the conductor. The forced convection is very dependent on the angle of attack on the conductor, the wind velocity and the temperature difference between the conductor and its surroundings. Usually the larger of natural and forced convection is used to estimate the convection cooling of the conductor [42, 100, 102].

Radiation Cooling

Radiation from a conductor to the surroundings is dependent upon the temperature difference between conductor and surroundings, the diameter of the conductor and the emissivity of the conductor surface [42, 100, 102].

Parameters used for Thermal Rating

The algorithms behind the thermal rating of conductors have not been directly presented here however the assumptions made for determining the thermal rating needs to be presented.

Table 6.16: Parameter Values used for Thermal Rating.

Variable	Value	Unit	Used for
Ambient temperature	20	°C	Radiation and convection
Wind speed	0.6	m/s	Forced convection at a 90 ° angle to the line
Absorptivity	0.2 - 0.9		Factor for solar heating (low for new conductor and high for older or surface treated conductors)
Emissivity	0.2 - 0.9		Factor for radiation (low for new conductor and high for older or surface treated conductors)
Solar intensity	≈ 1000	W/m	Solar heating (calculated based on date in IEEE method)

The parameters in table 6.16 may vary dependent on geographical location and are here based on the conservative assumptions made for application in Denmark. Notice that the values are chosen to give a conservative estimation of the thermal rating. Thus full solar heating, low wind during full utilisation of the current capacity of the line is a rare occurrence but even under these conditions the clearance to grounded objects must be kept. Cigré have published a brochure that can aid in the selection of weather parameters for conductor thermal ratings, see [123].

6.2.3.2 Emergency Operation

Under normal operation only the steady state current-temperature relationship of the conductor is of interest. There is however a time-delay in the temperature response of a conductor to a change in the current running in the line.

The time-delay in the temperature response of the conductor can be utilised under emergency operation of the line. Currents greater than the thermal rating current can be allowed to flow in the conductor for a short period of time without increasing the conductor temperature beyond the maximum design temperature due to time lag in the temperature response. This will be examined closer in the section on Temperature Rise during Emergency Loading below.

Besides knowing the temperature development under emergency operation it is important to investigate the temperature development under fault currents. This takes place under adiabatic conditions where no energy exchange with the surrounding can take place. The current temperature relationship under faults currents for composite conductor will be presented below.

Temperature Rise during Emergency Loading

Under emergency loadings heat storage in conductors needs to be considered for the current-temperature relationship. Thus energy balance equation presented earlier is unchanged.

$$Q_S + I^2 R_{AC} = m \cdot C \frac{d\theta}{dt} + Q_C + Q_R \tag{6.32}$$

The energy balance can be rearranged into the following equation.

$$\frac{d\theta}{dt} = \frac{1}{m \cdot C} \left(R \cdot I^2 + Q_S - Q_C - Q_R \right) \tag{6.33}$$

The solution to the equation above can be approximated to the following expression. The equation is illustrated in figure 6.4. The time, t, where the temperature is θ is dependent on the initial temperature before the current step, θ_l, and the final temperature at steady state after the current step, θ_m.

$$t \approx -\frac{mc\theta_m}{I^2 R_{AC} + Q_S} \cdot \ln\left(\frac{\theta_m - \theta}{\theta_m - \theta_l}\right) = \tau \cdot \ln\left(\frac{\theta_m - \theta}{\theta_m - \theta_l}\right) \tag{6.34}$$

$$\theta = \theta_m - (\theta_m - \theta_l)\, e^{-\frac{t}{\tau}} \tag{6.35}$$

The initial and final temperatures are calculated by use of the steady state equation for the current before and after the current step. The equation above is used to calculate how the temperature changes with time as a result of the current step.

When the loading of a conductor is changed from one current level to another an unsteady state will arise. The temperature of the conductor will change; decreasing with reduction in loading and increasing with larger loading.

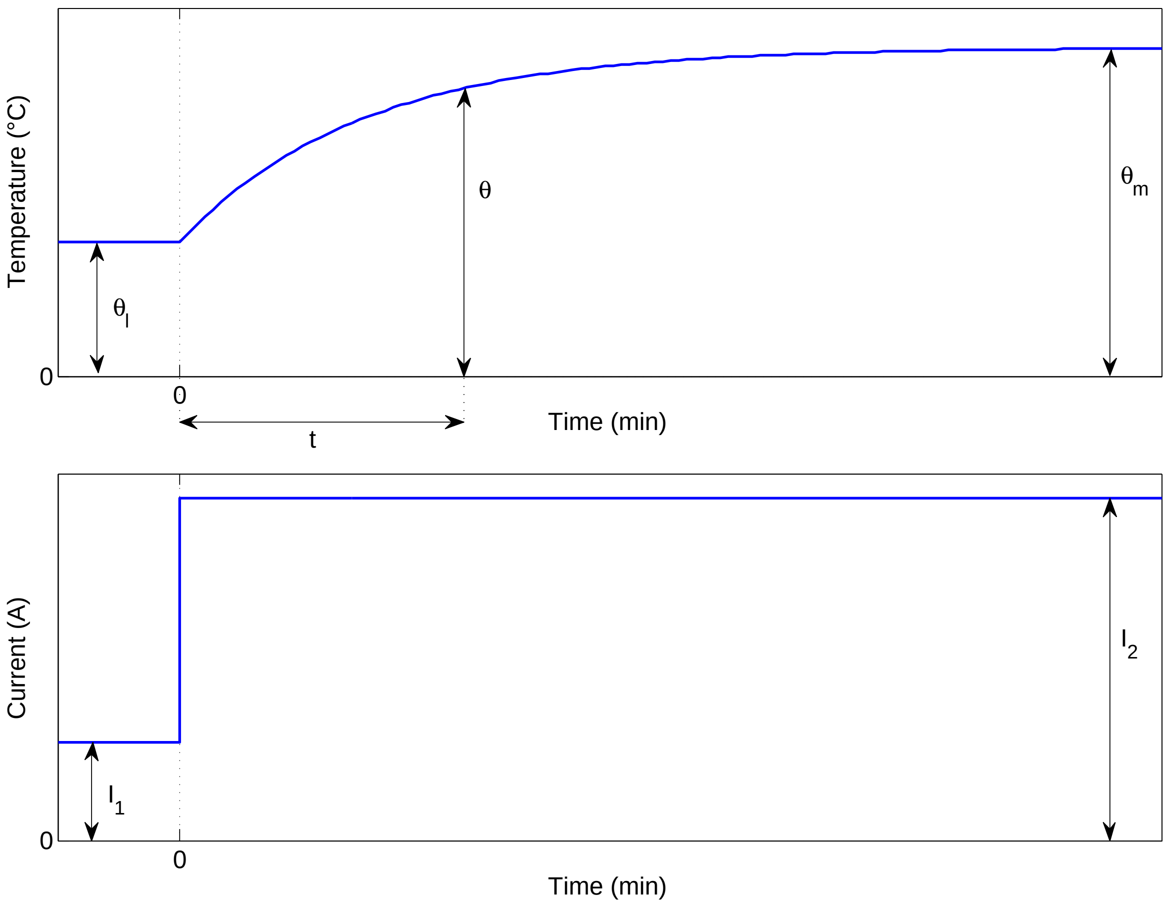


Figure 6.4: Temperature response to current step change.

In reality many of the parameters used to calculate the temperature change under unsteady-state will not be constant. Ambient temperatures will change depending on time of day and heating by the sun. Also the current loading of the line will have fluctuations before a steady state will occur again. The calculation of current rise under current steps does thus not reflect the reality but could however give an idea of over which times cooling and heating of a conductor occur [100, 102].

Temperature Rise during Fault Currents

During fault currents, the current in a conductor can reach values of over 10 kA during a time interval up to 1 second. To ensure that the conductor is not subjected to harmful temperatures the current-temperature relationship under fault currents must be investigated. Due to the short time and the larger amount of power the system will be in adiabatic state and thus not exchange energy with the surroundings. Thus all of the heating due to the ohmic heating must be stored in the conductor.

Under adiabatic state, the energy balance of the conductor will be reduced to the following equation.

$$I^2 R_{AC} = m \cdot C \frac{d\theta}{dt} \tag{6.36}$$

By integration of the equation above the following equation can be reached.

$$\frac{1}{\alpha} \ln \frac{1 + \alpha (\theta_2 - 20)}{1 + \alpha (\theta_1 - 20)} = \frac{I^2 \rho_{dc}}{A (A_1 \gamma_1 c_1 + A_2 \gamma_2 c_2)} t \tag{6.37}$$

Based on the equation above the temperature θ_2 at time t at a fault current I can be estimated based on the temperature θ_1 before the fault current, the resistivity ρ_{dc} of the conductor and the thermal capacity $A_1 \gamma_1 c_1 + A_2 \gamma_2 c_2$ of the conductor.

In the Cigré guidelines for calculation of conductor temperature during transients a maximum temperature of 200 °C is recommended for mechanically stressed conductors (with the exception of pure steel conductors, where the limit is 300 °C).

Radial Temperature Gradients

Along the radius of a conductor there will be a temperature difference. The core will run hotter than the conductor surface as there need to be a heat transfer from the core to the surface and then to the surroundings.

The radial temperature difference – the difference between the temperature at the core θ_C and at the surface θ_S – can be estimated from the total heat gain, P_T, the radial thermal conductivity, λ, the core and overall conductor diameter, D_i and D respectively. The main value for the thermal conductivity is approximately 2 W/mK [102].

$$\theta_C - \theta_S = \frac{P_T}{2\pi\lambda} \left(\frac{1}{2} - \frac{{D_i}^2}{D^2 - {D_i}^2} \cdot \left(\ln \frac{D}{D_i} \right) \right) \tag{6.38}$$

The radial thermal conductivity is determined by the properties of the aluminium and should therefore be directly transferable to composite conductor, since only the core material is changed compared to ACSR conductors.

Radial Temperature Gradients in Composite Based Conductors

For standard steel aluminium conductors, radial temperature gradients are only an issue with regard to a slight increase in the sag of the conductor. This is caused by the fact that for thermal ratings of conductors the surface temperature is normally the temperature used while the sag of a conductor will be mostly dependent on the core, since the core carries the greater part of the mechanical load. Furthermore it is the aluminium that limits the temperature at which ACSR conductors are normally operated to avoid annealing of the aluminium. For high temperature low sag conductors the core of the conductor can still tolerate higher temperatures than the aluminium.

For the composite based conductors however there could be a concern regarding the temperature limits set for the conductors as discussed in section 5.2.4.1. For the ACCR conductor the core is made of aluminium fibres imbedded in an aluminium matrix. The operating temperature is limited to 210 °C under normal operation due to the zirconium-aluminium strands used for the conductor layer. If the conductor is driven at this temperature the core could reach higher temperatures than 210 °C according to figure 6.5. However at this temperature range the core should not be severely affected by the temperature and emergency operation up to 240 °C is allowable according to the manufacturer, however the temperature limitation are primarily set to ensure the mechanical strength of the zirconium-aluminium strands.

For the ACCC conductor the temperature limit is set to 180 °C by the manufacturer. However for the ACCC conductor it is not the mechanical integrity of the aluminium strands that are the concerns since annealed aluminium is used. Instead it is the integrity of the core that limits the temperature range of conductor. If the conductor is operated at 180 °C then the core will run hotter according to figure 6.5. If this is coupled with the findings in [41] this concern might be justified. In [41] degradation of the fibreglass sheath covering the carbon core starts at approximately 140 °C and at 150 °C for the core. The degradation is low at these temperatures and develops rapidly at over 200 °C for the fibreglass sheath and at over 300 °C for the carbon core.

For neither the ACCC nor the ACCR conductor test of the mechanical strength as a function of temperature are public available. However the findings in [41] could indicate that the ACCC conductor's strength will begin to deteriorate at temperatures above 150 °C and deteriorate rapidly at around 250-300 °C. It is therefore important to consider the radial temperature and the temperature of the core if the conductor is operating near its maximum continuous operating temperature of 180 °C.

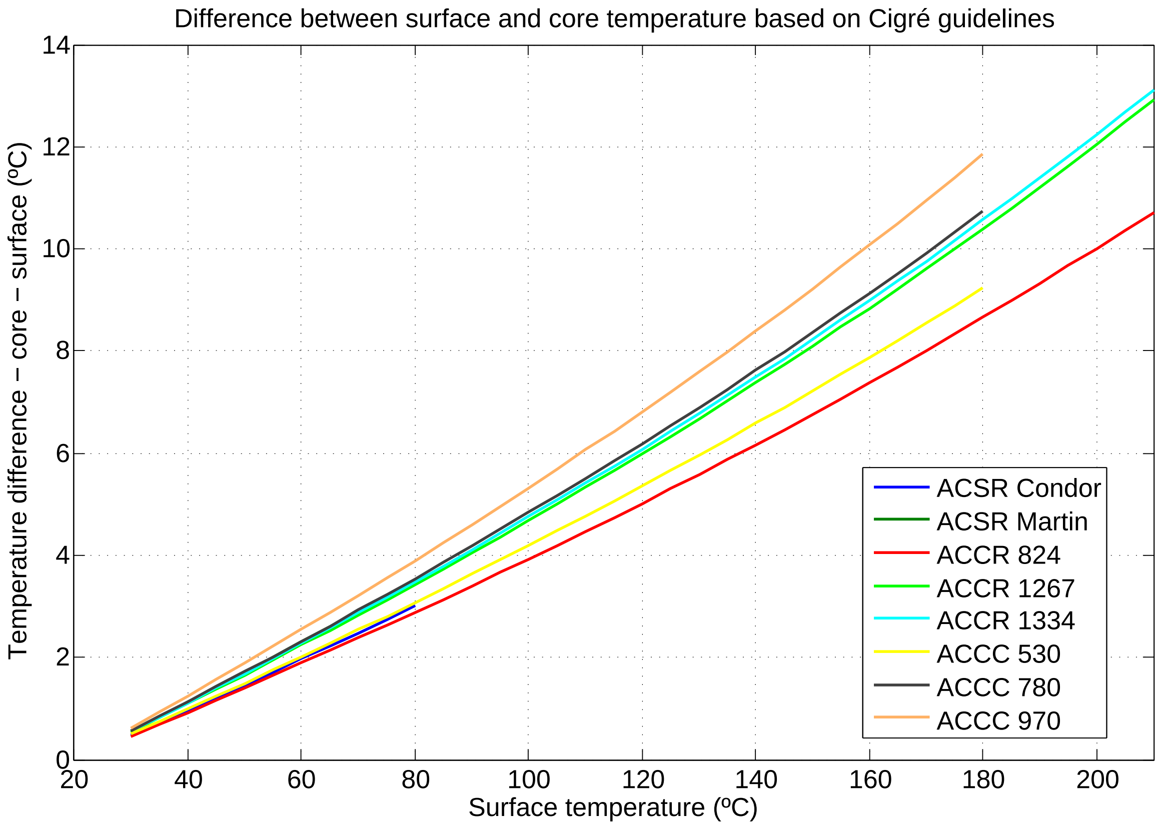


Figure 6.5: Temperature difference between core and surface temperature of selected conductors based on Cigré guidelines [102].

6.3 Loading of towers and insulators

Design of mechanical strength of towers and insulators can like insulation coordination for the electrical strength be based on statistical data or empirical data from experience with constructing overhead line systems. In practise a combination of the these approaches are used (again much like insulation coordination for insulation strength).

In the European standard for overhead lines it is stated that an overhead line must perform under a defined set of conditions with acceptable levels of reliability and costs. The line must not be subject to cascading faults and it must not cause loss of human life or injuries during construction and maintenance. Furthermore an overhead line must operate without danger to the general public and with consideration to the environment.

Overhead lines must be able to cope with several different load types as already presented for overhead line conductors. However for full design components must be able to handle the climatic loads in-service consisting of wind forces and ice loads as well as loads caused under construction and maintenance. For more information refer to [99].

6.3.1 Partial Factors

The above stated demands have among other things lead to that for design of the mechanical strength of overhead lines, partial factors are used to ensure adequate mechanical strength of the overhead line components. Thus the design load of a force can be expressed by the following equation.

$$F_d = \gamma_F \cdot F_K \tag{6.39}$$

The design load, F_d, of a force equals the predicted load, F_K, multiplied by the partial factor for the component the force is acting on, γ_F. Besides the forces acting on the system also the strength or strength resistance of the individual components must be known. The characteristic resistance, R_K, of a component is divided by a material partial factor, γ_M, whereby a design value for the components resistance, R_d, is reached as stated in equation (6.40). This is done again to ensure that the overhead line design can operate safely and reliably.

$$R_d = R_K/\gamma_M \tag{6.40}$$

For the dimensioning of an overhead line the combined design loads, E_d, acting on a component must be coordinated with design components design resistance, R_d, ensuring that equation (6.41) is true [42].

$$E_d \leq R_d \tag{6.41}$$

As stated the partial factor is dependent on which component is being designed and in some cases also the material. A selection of the partial factors mentioned in EN50341 is given in table 6.17 for comparison.

It should be noted that many other partial factors are used depending on the application. In examples holes for bolts and rivet in steel structures have separately specified partial factors to ensure sufficient mechanical strength. Furthermore for some load situations further partial factor are specified. For more information refer to [99].

In table 6.17 it can be seen that for conductors and insulators a single partial factor is given without any dependency on material. For towers, the partial factors is though dependent on material but no values are stated for any types of composite material. Suggestions for partial factors for composite based structures will not be given here but the selection of partial factors should be made based on applicable standards and experience with the specific composite material.

Table 6.17: Selected partial factors (γ_M) for overhead line components and materials applied in EN 50431-1 for mechanical load design [99].

Component	Partial factor
Insulator	2.00
Conductor	1.25
Tower incl. crossarms	
Timber	1.50
Steel – pole	1.10
Steel – lattice tower	1.10
Concrete (steel)	1.50 (1.15)

6.3.2 Load cases

Components of overhead line system are subjected to a multitude of different load and load combinations. The design value of the forces acting on a components is calculated based on equation (6.42) where the different types of forces that need to be considered (G, Q or A) are specified along with their partial factors (γ).

$$E_d = \sum (\gamma_G G_K + \gamma_W Q_{WK} + \gamma_I Q_{IK} + \gamma_P Q_{PK} + \gamma_C Q_{CK} + \gamma_A A_K) \tag{6.42}$$

The design load is calculated based on self-weight loads, G_K, wind loads, Q_{WK}, ice loads, Q_{IK}, conductor tensile loads, $Q_P K$, construction and maintenance loads, Q_{CK}, and exceptional/security loads, A_K. Depending on the loading situation different combination of the forces in equation (6.42) are used. In EN50341-1 several load cases are presented to represent the different loading situation of overhead line components. The are listed in table 6.18.

Table 6.18: Load cases for overhead lines given in EN50341-1 [99].

Load case	Conditions
1a	Extreme wind load
1b	Wind load at a minimum temperature
2a	Uniform ice loads on all spans
2b	Uniform ice loads, transversal bending
2c	Unbalanced ice loads, longitudinal bending
2d	Unbalanced ice loads, torsional bending
3	Combined wind and ice loads
4	Construction and maintenance loads
5a	Security loads, torsional loads
5b	Security loads, longitudinal loads

The design value of the forces must further take into the consideration the direction of the forces ensuring that forces are analysed in the vertical and horizontal place respectively. Vertical loads can consist of loads due to the weight of individual components and ice loads and horizontal loads can consist of wind loads on components and unequal tensions in conductors.

Besides wind and ice loads also construction and maintenance loads and security loads are included in the load cases for overhead line cases (table 6.18). The construction and maintenance loads consists of the extra loads that might be applied to an overhead line system during construction and maintenance. To ensure the safety of line the partial factors for these loads amongst the highest used in the design. The security loads consist of different failure situations where the breakage of line conductors may result in torsional and longitudinal loads on towers and insulators.

An example of partial factors for the forces are presented in table 6.19 based on Danish NNA in EN50341-3 [115].

Table 6.19: Load partial factors in the Danish NNA of EN50341-3 [115].

Loads	Symbol	Value
Component weights	γ_G	1.0
Wind loads	γ_W	1.4
Ice loads	γ_I	1.5
Ice loads combined with	γ_I	1.5
wind loads	$\Psi_W{}^*$	0.4
Construction and maintenance loads	γ_P	1.5
Torsional security loads	γ_{A1}	1.5
Longitudinal security loads	γ_{A2}	1.0

* Wind factor for combined wind and ice loads

For more information, including how to calculate wind forces and ice loads on overhead line components, [99], [115] and [42] should be consulted.

6.3.3 Loading of Beams

Insulators, crossarms and towers in overhead line can be considered for mechanical purposes as beams and based on this, their ability to carry mechanical loads will be described in short below.

6.3.3.1 Bending of Beams

Bending of beam can be described by the Euler-Bernoulli equation more commonly known as the beam equation. The deflection of a beam, u, is depended on the stiffness (elasticity modulus) of the beam, E, the area moment of inertia of the beam, I, the position along the length of the beam, x, and the distributed load, w, on the beam as stated in equation (6.43).

$$\frac{\partial^2}{\partial x^2}\left(EI\frac{\partial^2 u}{\partial x^2}\right) = w \tag{6.43}$$

Often the stiffness and the area moment of inertia is constant or can at least be considered constant. Thus equation (6.43) can be transformed into a function of the position along the beam, x.

$$EI_M\frac{d^4u}{dx^4} = w(x) \tag{6.44}$$

Post insulator and pole towers are examples of cantilever beams, i.e. a beam fastened at one end with a load acting at the other end of the beam. The maximum deflection of a cantilever beam can be calculated from equation (6.45) which is based on integration of equation (6.43).

$$u = -\frac{P \cdot {L_B}^3}{3EI_M} \tag{6.45}$$

The stress in the beam to a position c_x in relation to the neutral axis at x can be calculated from the bending moment, M, and area moment of inertia, I_M, of the beam.

$$\sigma = \frac{Mc_x}{I_M} \tag{6.46}$$

At the neutral axis of the beam, the stress due to bending moments in the beam is zero. As the distance to the neutral point is increase so is the stress in the beam. Thus the stress in a pole or insulator will be greatest at surface at the connection to either the end fitting for insulators or at the foundation for pole towers.

6.3.3.2 Buckling of Beams

For buckling of components under compression, Euler's formulae can be used; a beam or column with one end free and the other fixed will buckled at the critical load, P_{cr}, which is dependent on the columns elasticity modulus, E, its area moment of inertia, I_M and the length of column or beam, L_B.

$$P_{cr} = \frac{\pi^2 EI_M}{4{L_B}^2} \tag{6.47}$$

Thus the buckling of a beam or column is very dependent on the length of the component. As a components is elongated, the force leading to buckling lessens, unless the dimensions and thereby the area moment of inertia is increased [24].

6.3.3.3 Area moment of inertia

The area moment of inertia or moment of inertia is a geometry dependent factor. In equations (6.48) and (6.49) the area moment of inertia for a beam of circular and cylindrical cross section are stated.

The area moment inertia of a beam with a circular cross section (e.g. the core rod of an insulator) is dependent on the radii, r, of the beam.

$$I_M = \frac{\pi r^4}{4} \tag{6.48}$$

For a cylindrical beam the area moment inertia is dependent on the inner and outer diameter, d_i and d_o respectively, as stated below.

$$I_M = \frac{\pi \left({d_o}^4 - {d_i}^4\right)}{64} \tag{6.49}$$

6.4 Analysis – Dimensioning of Composite Components

The dimensioning of overhead line systems is dependent on a multitude of different factors. Among these the choice of overhead line conductors is though of the factor with the largest impact as conductor weight and tension will influence the mechanical design of towers and insulators. Furthermore the sag of conductors will influence the electrical clearances and the top geometry as well as pose demands for tower height to ensure adequate clearance to ground.

With this in mind calculations on sag-current relationship of composite based conductors and clearance requirements for EHV systems will be carried out in the following subsections. How demands for clearance will affect the mechanical design of overhead line components will subsequently be discussed.

6.4.1 Sag-Current Relationships of Composite Based Conductors

In the following sections, the sag-tension and sag-temperature relationship of the conductors listed in table 4.3 will be presented and analysed with regard to the level of sag dependent on current carried by the conductor.

6.4.1.1 Sag-Tension Calculations for Selected ACCC, ACCR and ACSR Conductors

In the following sag-tension calculations for a selection of conductors have been carried out. The calculations are based on the STOC method described in appendix A.

For actual applications of conductors to overhead lines it is common to use full parameterised models. In full parameterised models the relations between stress and strain in the conductor is based on equations for both loading and unloading of the conductor. Here however the stress-strain relation of the conductor will be described by the final elasticity modulus during unloading which represents the relation between stress-strain of a pre-loaded conductor.

The sag of the selected conductors are done at the loading cases prescribed by EN50341-3 (Danish NNA – listed in table 6.13) with the exception of wind loads. The sag at temperatures from 0 °C to maximum continuous operating temperature will also be listed so that the chosen maximum design temperature (MDT) is also covered. The maximum operating temperatures of the different conductors are summarised in table 6.20.

Table 6.20: Maximum operating temperature of ACSR, ACCR and ACCC conductors [40, 42, 43].

Conductor	ACSR	ACCR	ACCC
Maximum continuous operating temperature	80 °C	210 °C	180 °C
Emergency operating temperature	100 °C	240 °C	200 °C

Furthermore the sag-tension calculations are carried out for a 300 m level span. The span length and whether it is level or not also affect the sag of the conductor and should therefore be examined based on the actual span where the conductor will be used. Here however a 300 m level span is used for comparison.

The calculations are carried out with an ambient temperature of 15 °C, which is also taken as the stringing temperature. For the ACCC and ACCR conductors the aluminium is assumed to be slack at stringing. For ACSR the stress is assumed equal over the entire cross section of the conductor at the stringing temperature.

The sag of the conductor are calculated based on three different initial stringing stresses; 65 N/mm2, 55 N/mm2 and 20 % rated tensile strength (RTS). In Denmark the values 65 N/mm2 and 55 N/mm2 are typically used based on whether or not damping equipment is installed on the line. If dampers are installed a value of 65 N/mm2 can be allowed else 55 N/mm2 is used. Some countries base the stringing stress (or force) on the rated tensile stress of the conductor. 20-25 % of the rated tensile strength is normally recommended. This limit is also often used as a recommended daily stress on the conductor. Sag in all three cases is shown below.

The sag of the different conductors is calculated up to their maximum continuous operating temperature. This is done to give an impression of the relation between the temperature and the current rating of the different conductors and to compare the sag of the different conductors at the same temperature.

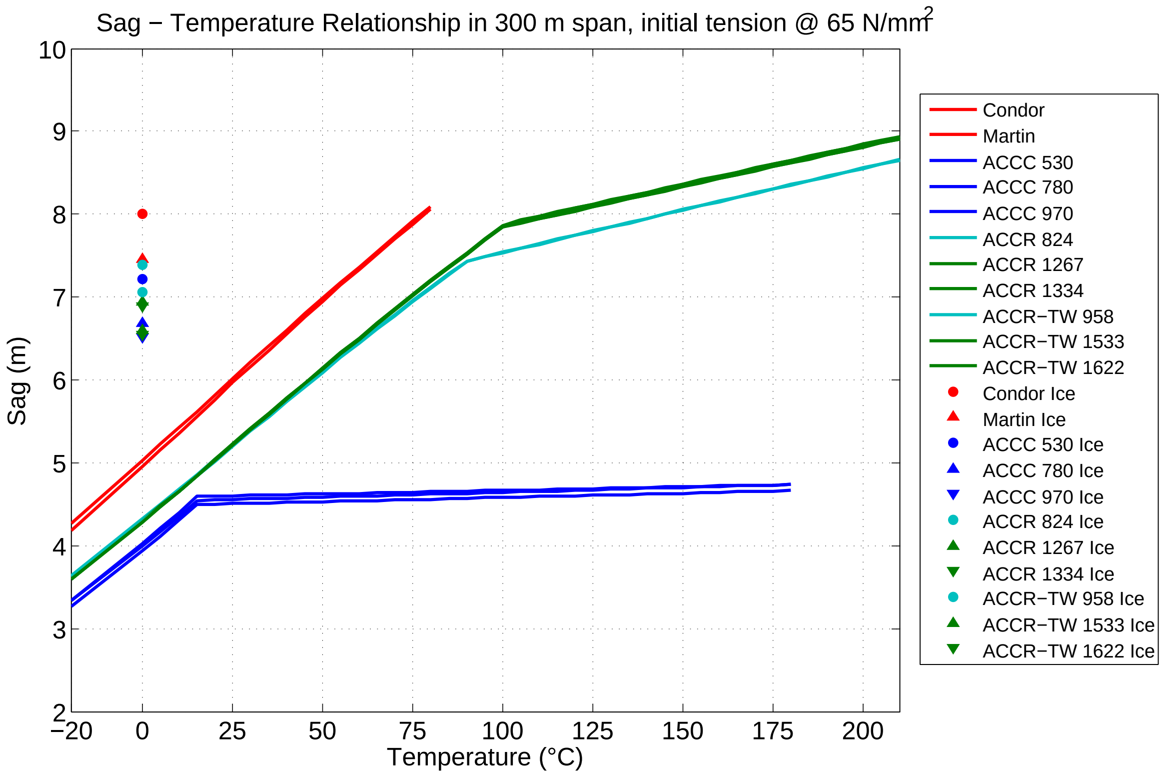


Figure 6.6: Sag of selected conductors for a 300 m span at an initial stress of 65 N/mm^2, including ice load according to equation (6.27).

From figures 6.6 and 6.7 it can be seen that the conductors of the same type have the same sag when installed at the same stress. This is because the actual tension of the conductors will vary with the cross section of the different conductors as does the conductor parameters. The parameters of the line and the sag calculations are dependent upon the cross section of aluminium to steel ration and the sag for the conductors with equal aluminium/steel ratio when installed at the same stress are thus equal. It is important

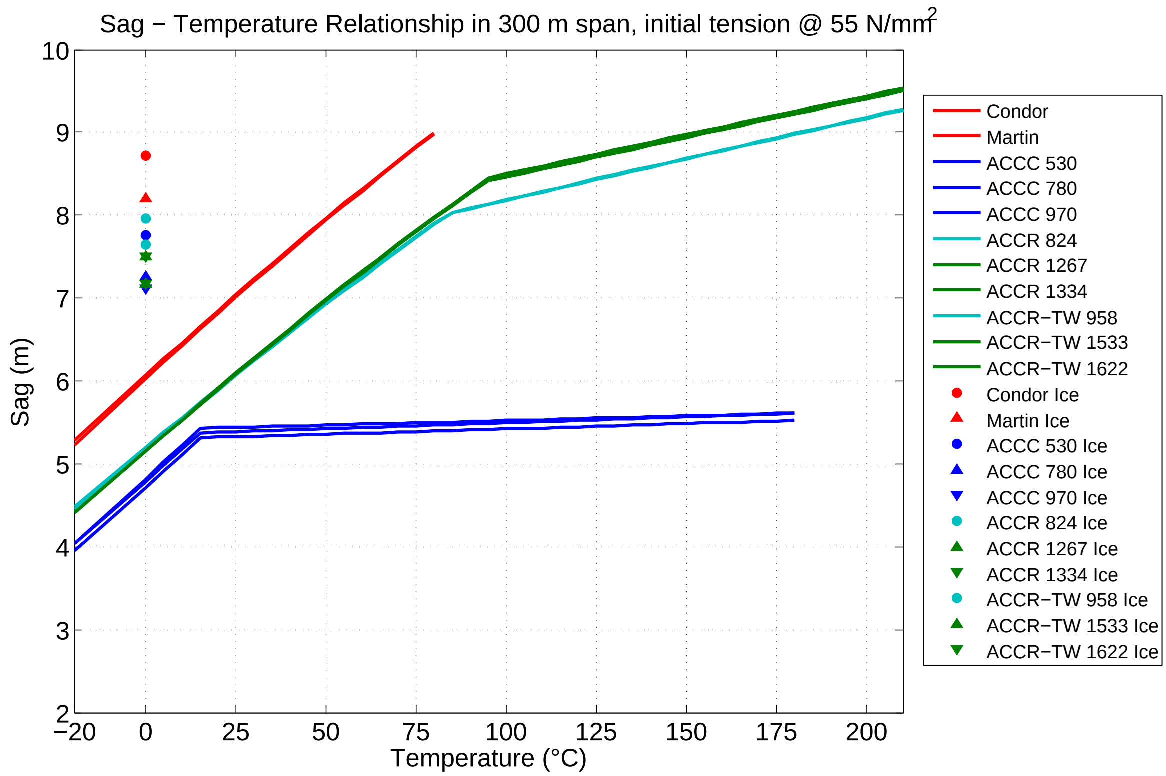


Figure 6.7: Sag of selected conductors for a 300 m span at an initial stress of 55 N/mm^2, including ice load according to equation (6.27).

to notice that it is the temperature-sag relationship that is equal for the same type of conductors. This however does not mean however that the conductors can carry the same amount of current at equal sags (the temperature of the conductors will be different at the same current). Furthermore the conductors will also have different sags under ice loads as can be seen from the figures.

In figure 6.8, the different conductors' sag are calculated at 20 % rated tensile strength (RTS). This results in different stresses for the conductors and different sag profiles. For some of the conductors the sag-temperature relationship is however still very similar.

From figures 6.6, 6.7 and 6.8 it can be seen that the ACCC and ACCR conductors have a more favourable relationship between sag and temperature than the conventional ACSR conductors. This due to the better conductor characteristics of the two conductors compared to ACSR. For the ACCC conductor, the advantage of using annealed aluminium is quite clear. The ACCC conductor will have a thermal kneepoint at its installation temperature. Above the thermal kneepoint, the core carries the entire load whereby the conductor elongation is only dependent on the low thermal expansion and the stiffness of the core. The kneepoint of the ACCR and ACSR conductors will appear later than for the ACCC conductor, as the aluminium is part of the mechanical load carrier up to

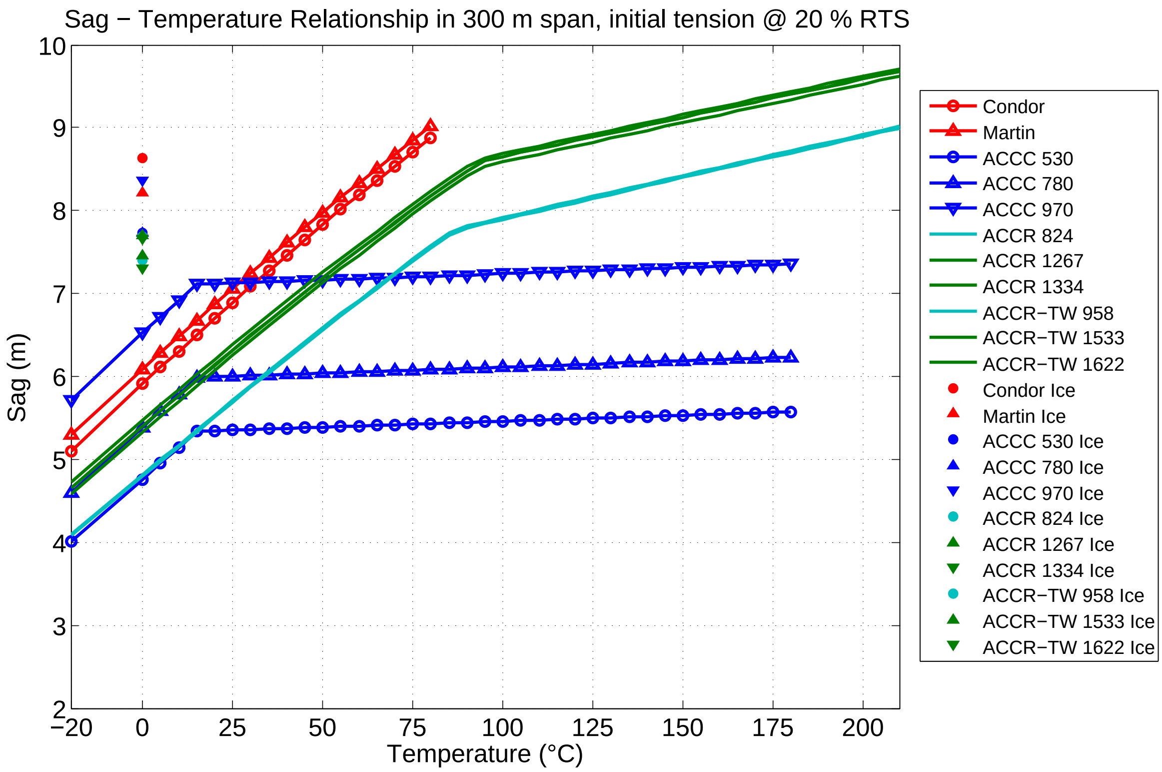


Figure 6.8: Sag of selected conductors for a 300 m span at an initial tension of 20 % RTS, including ice load according to equation (6.27).

the kneepoint where the core will carry the entire mechanical load as the aluminium have elongate to much compare to the core to contribute to the strength. The kneepoint is still exploited by the ACCR conductor as the conductor can operate at temperatures more than double the value of the kneepoint temperature. The ACSR conductor at the limited temperature of 80 °C does not utilise the lower sag increase above the kneepoint.

It should be noted here that use of ACSR conductors of other diameter than the here chosen and with other aluminium/steel ratios could perform better than the Condor and Martin conductors used in the present work. Furthermore other conductors, as previously mentioned in section 4.1.2.2 are available and could in a specific case be more preferable than ACCC and ACCR conductors.

When considering which conductor to install it is important to calculate the sag not only at the maximum operating temperature but also under ice load conditions. In the three figures above the sag under ice load at 0 °C is included. These are the upper most cluster of sags at 0 °C in the figures. For the ACSR and the ACCR conductors the greatest sag is achieved at the maximum temperatures of 80 °C and 210 °C and thus the ice load does not play role when designing the line with respect to clearances. The sag at ice load is 0.5-1.0 metres lower than the sag at 80 °C for ACSR Condor and Martin conductors. For the ACCC conductors the maximum sag is however not achieved at the maximum operating temperature but at the ice load. This seriously affects the difference in maximum sag between ACCC and ACCR conductors, the ACCC conductors do still though achieved the lowest sag. Furthermore the great difference in sag between ACSR and ACCC conductors is also reduced to the point where if restricted a temperature range 80 °C, the ACCC conductors when considering ice load will not offer the possibility of lower sag of the line. The ACCC and ACCR conductors do perhaps not offer better sag characteristics with regard to ice loads but the both conductors will allow a greater temperature range and therefore also larger currents in the conductor.

A further comparison is made in figure 6.9 between the ACSR, ACCC and ACCR conductors. In the figure the result of sag calculations, where the ACCC and ACCR conductors are installed at the same initial tensions as the ACSR conductors of the same diameter (corresponding to 29510 N for the ACSR Condor and 50180 N for the ACSR Martin), are shown.

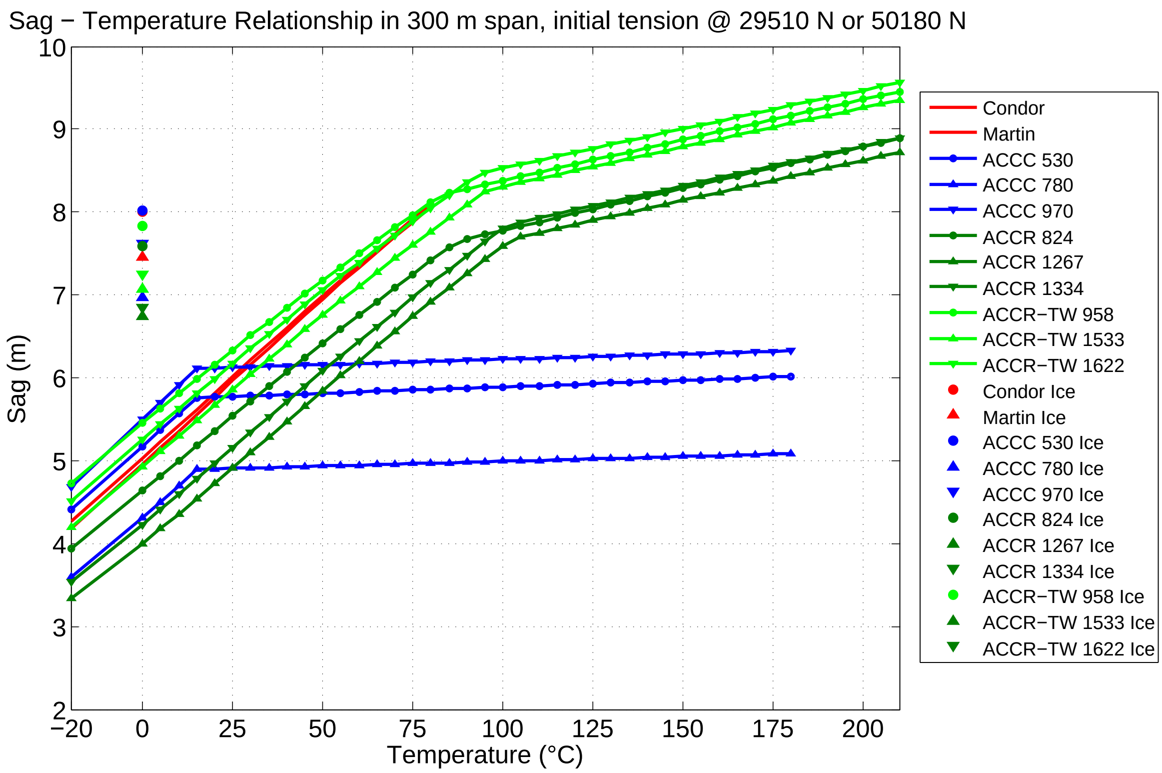


Figure 6.9: Sag of selected conductors for a 300 m span at an initial tension of 29510 N or 50180 N, including ice load according to equation (6.27)

For the ACCR-TW conductors the same sag-temperature profile is achieved until the ACSR conductor temperature limit. The ACCR-TW would therefore not offer any advantages compared to ACSR at the same tension if the same sags where to be kept. The ACCR conductors with round aluminium wires offer a sag reduction compared to the

ACSR conductors of approximately a half to one metre at the same temperatures and would therefore allow higher temperature operation and thus greater loadability of the line. Though not to the full temperature limit of the ACCR conductor. The ACCC conductor dependent on the size offers zero to half a metre in sag reduction due to the ice loads on the conductor. At the same time, the full temperature range of the conductor can though be used as a consequence of the low sag development with temperature.

In summery ice loads are important when evaluating sag of ACCC and ACCR conductors. ACCC and ACCR conductors have a lower sag than same diameter ACSR conductors at the same temperature. However the sag under ice load conditions is not as drastically reduced. Under ice load conditions the sag of the ACCC and ACCR conductors are only approximately 0 m - 1 m lower than ACSR conductors of the same diameter depending on the initial tension conditions. This is in accordance with [124].

6.4.1.2 Current-Temperature Calculations for Selected ACCC, ACCR and ACSR Conductors

Current-temperature calculations for ACCC, ACCR and ACSR conductors are presented in the following (notice that ACCR-TW are not included). The calculations are based on weather parameter recommendation by Cigré and IEEE and are listed in appendix B.

The current-temperature curves are calculated from 30 °C to the maximum continuous operating temperature of the conductors. The actual current rating – current allowed at maximum temperature – of a line depends on the design conditions. Conservative design conditions are used to ensure that the conductor do not experience temperature above the maximum continuous operating temperature under normal conditions. The sag-temperature curves based on Cigré's calculation methods are presented in the following.

In figure 6.10 it can be seen that the ACCC 970 Antwerp conductor gives the highest ampacity of the different conductors. It is followed by the ACCC 780 London, ACCR 780 Martin, ACSR Martin and ACCR 1267 Pheasant which all give a similar ampacity. A second group of conductors with similar current-temperature relationships consists of the ACCC 530 Warsaw, ACCR 824 Drake and ACSR Condor. The reason that these groups exist is that the conductors in each group have very similar diameters which is an important parameter when determining radiation, convective cooling and solar heating of the conductors. Furthermore the diameter of the conductors play a role with respect to the resistance of the conductor. Thus the diameter is one of the main factors in conductors' current-temperature relationship.

The ACCC conductors generally offers a higher ampacity within the two different groups despite the ACCR's higher temperature limit. This is mainly caused by the composition of the ACCC conductors where trapezoidal shaped aluminium wires are used instead of round aluminium wires. This gives a higher fill factor or aluminium per cross section. Thus the resistance of the ACCC conductors is lower than that of ACSR and ACCR conductors of the comparable diameter allowing more current at less heat development.

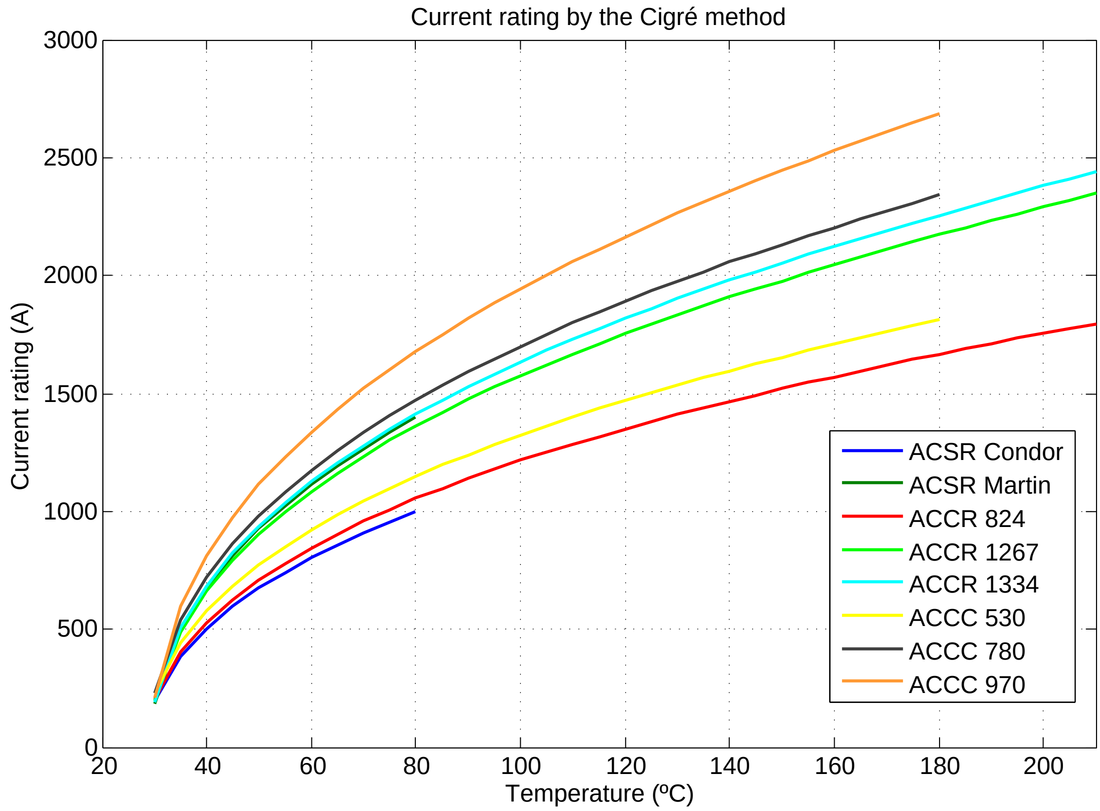


Figure 6.10: Current-temperature relationship of selected conductors based on the Cigré calculation method [102].

Both the ACCC and ACCR conductors allow much greater current loading (loadability) than the ACSR conductors, as the ACSR conductors are limited to more than half the temperature limits of the ACCC and ACCR conductors. In general the current rating goes from 1000 A and 1400 A for ACSR Condor and ACSR Martin respectively to 1750 A and 2400-2700 A for the ACCC and ACCR conductors.

The relation between the sag of a conductor and the current carried by the conductor will be compared for the selected ACSR, ACCC and ACCR conductors in section 6.4.1.3.

Comment on Cigré and IEEE Models

Only small differences exist between the Cigré and IEEE calculation methods ([102] and [100] respectively). The Cigré method tends to give a slightly larger ampacity than the IEEE method. However the small difference in results makes it relevant only to use one ampacity calculation in the present work. The Cigré ampacity calculation method is used for the calculations presented in the Thesis. The relative difference between the two models is shown in figure 6.11.

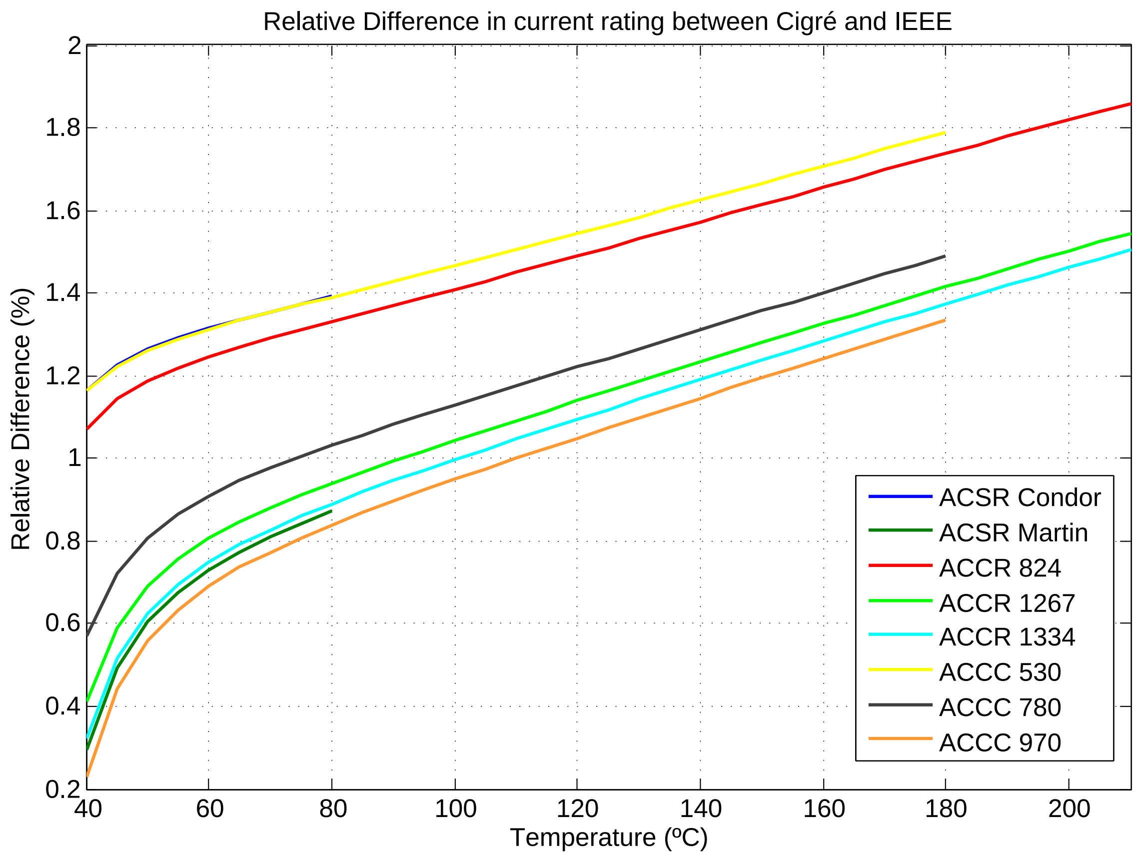


Figure 6.11: Relative differences in current-temperature models by Cigré and IEEE for selected ACSR, ACCC and ACCR conductors [100, 102].

6.4.1.3 Sag-Current Curves for Selected ACCC, ACCR and ACSR Conductors

To compare the sag-current relationship of the different lines, the results in sections 6.4.1.1 and 6.4.1.2 have been combined in figures 6.12 and 6.13. The figures are based on the sag of conductors at initial stress 65 N/mm^2 for figure 6.12 and at initial tension corresponding to 20 % RTS for figure 6.13.

At the tension condition applied for figure 6.12 it can be seen that both the ACCR and the ACCC conductors have a more favourable sag-current relationship than the conventional conductors. The ACCC conductor shows the absolute most favourable relationship due to the conductor having a low sag profile and having trapezoidal aluminium wires allowing more current at less heat. The ampacity of the ACCR conductor could be improved by used of the ACCR-TW type but this would however increase the weight of the conductor

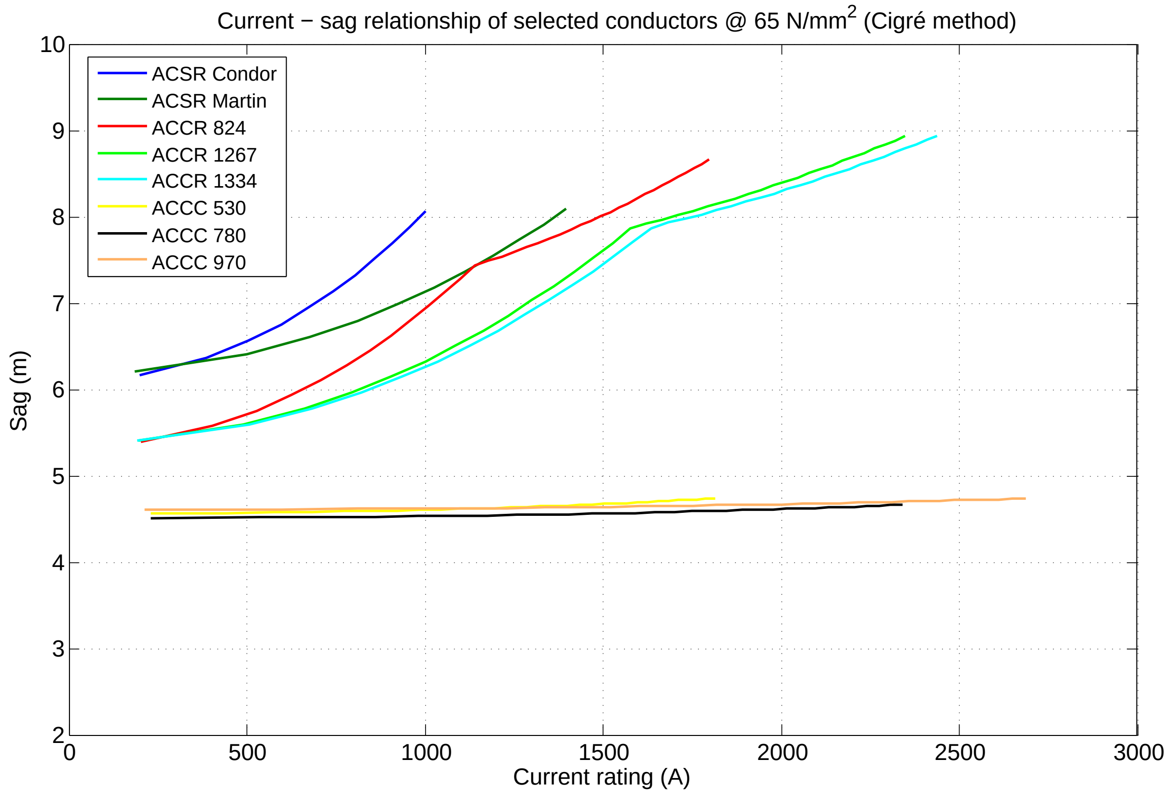


Figure 6.12: Sag-current relationship for selected ACSR, ACCC and ACCR conductors at 65 N/mm^2 initial stress based on the Cigré current-temperature model and the STOC sag-tension model [102, 125]

at the same time, thus decreasing the sag advantage to the ACSR conductor but still improving the loadability.

It was previously shown that when installing the ACCC conductor at 20 % RTS the sag of the conductor is increased due to the lower strength of the conductor. How this affect the sag-current relationship is shown in figure 6.13. It can be seen that greater dispersion between the ACCC conductors sag-current curves will be a result as the sag is increased more for the heavier conductors. Beyond a loading of a 1000 A the sag of the ACCC conductors are though still more favourable than the for the ACCR and ACSR conductors. For the ACCR conductor the consequences of using 20 % RTS are slightly higher sags as the tension in the conductor is lowered. At the same time the sag of ACSR conductor is improved as the tension is increased compared to a stress of 65 N/mm^2 resulting similar sag-current profiles of the ACSR and ACCR conductor. This is however only until the temperature limit of the ACSR conductor.

How much better the ACCR and ACCC conductors can be utilised is thus dependent on allowable sag of and tension in the conductors. The ACCR conductor is dependent on both of these factors and does not necessarily offer a better sag profile compared to

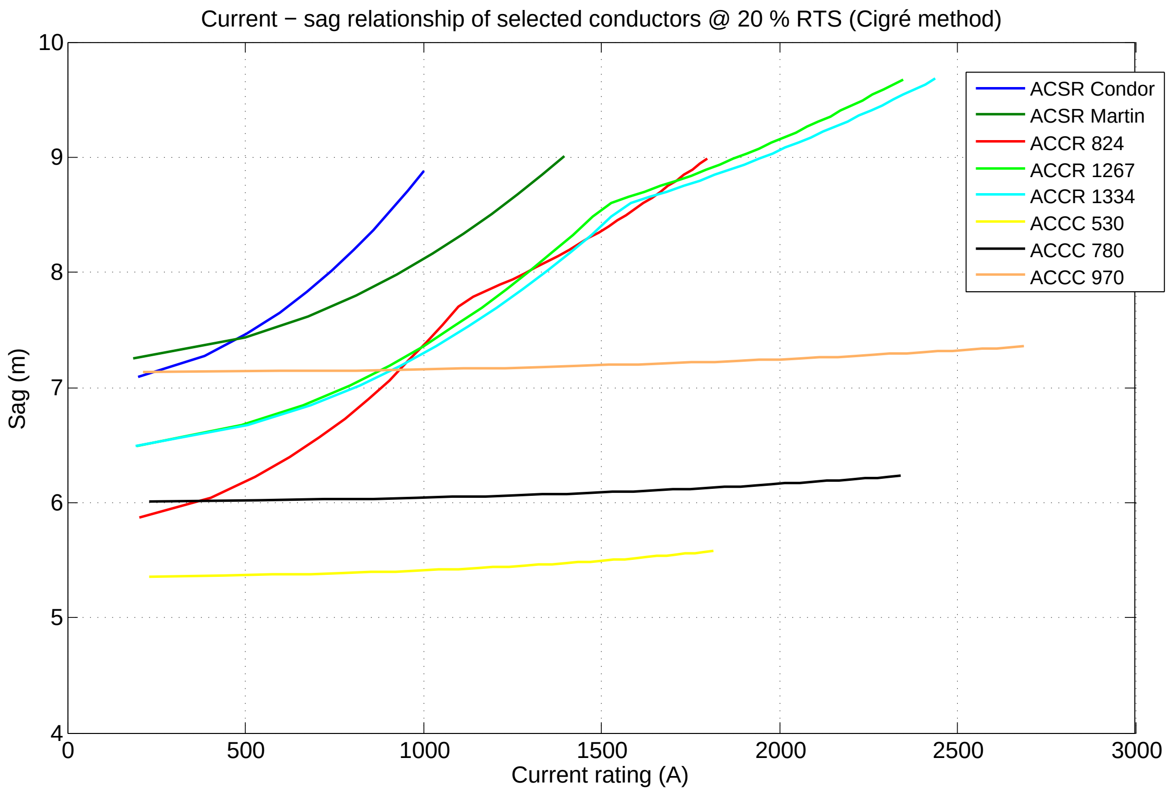


Figure 6.13: Sag-current relationship for selected ACSR, ACCC and ACCR conductors at 20 % RTS initial tension based on the Cigré current-temperature model and the STOC sag-tension model [102, 125]

ACSR conductors and can thus prove not to offer any advantages with regard to loadability compared to the ACSR conductor. The ACCC conductor will in most cases give better sag profiles than ACSR and ACCR conductors and allow full use of the conductor's temperature range due to the low thermal expansion of the core. Which conductor is best for actual implementation in an overhead line project will be case dependent.

6.4.2 Emergency and Fault Current Loading of Conductors

Besides the sag of the ACCC and ACCR conductors under normal operation it is also of interest to analyse the conductors behaviour under emergency and fault current loading and determine any advantages or disadvantages compared to ACSR conductors.

6.4.2.1 Emergency Loading

Recalling from section 6.2.3.2 emergency loading of a conductor results in an unsteady state where the conductor temperature will increase slowly after a current step until the energy balance for the conductor is restored. This is utilised for short periods of time in the operation of overhead lines allow higher currents than the current rating to pass through the line without infringing on the temperature limits of the conductor.

As an example the transient condition of a current step from 600 A to 1200 A for a selection of ACSR, ACCC and ACSR conductors are presented in figure 6.14. In the case of the ACSR Condor conductor this results in a to high temperature as the ampacity of the conductor is limited to 1000 A.

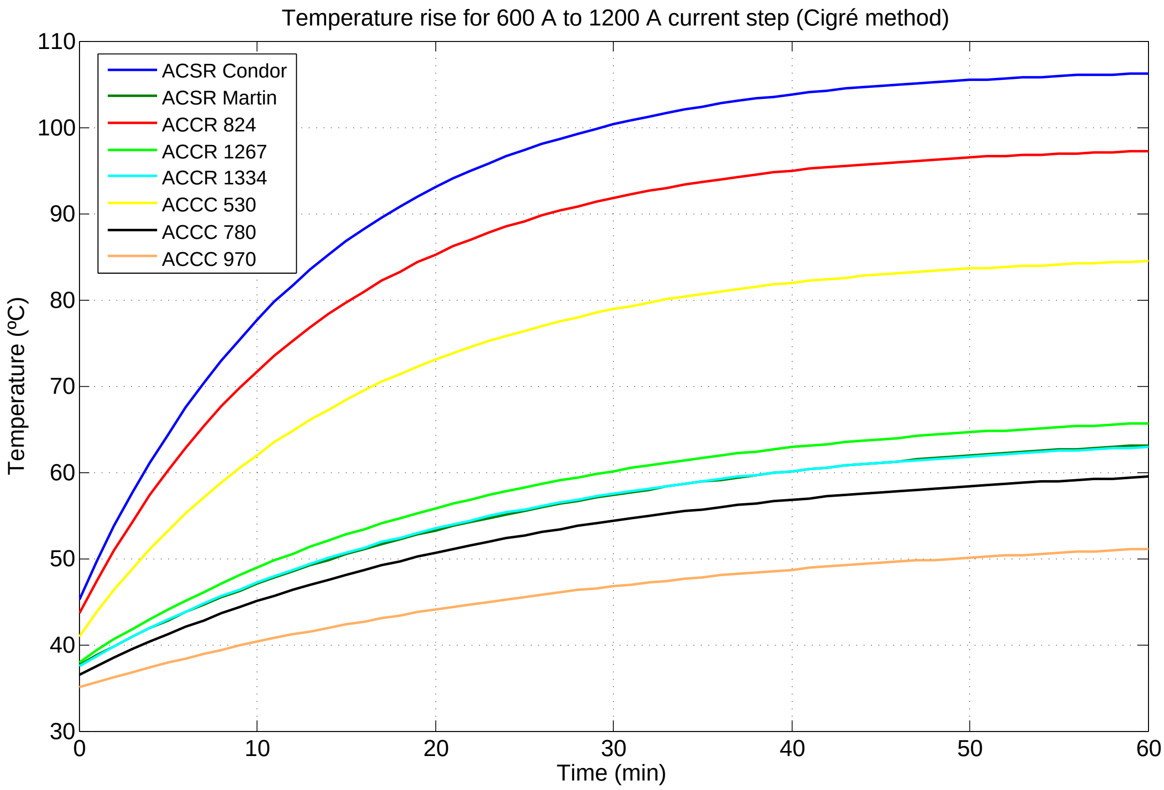


Figure 6.14: Temperature response of selected conductors to a current step change from 600 A to 1200 A based on Cigré guidelines [102].

From figure 6.14 it can be seen that the temperature time constant of the different conductors is very similar. The differences between the conductors are connected to the steady-state current-temperature relationship of the conductor as this determined the start and end points for the transient step. The figure does thus not show much.

In the operation of power systems under emergency conditions the lag in the temperature change related to current changes of overhead lines are utilised to allow overloading of overhead lines compared to the line's current rating. Typically a period of 15 minutes is used in which an overhead line can be overloaded up to its maximum emergency operation temperature allowing much needed capacity in a power system under emergency conditions.

The following calculation is made to illustrate such a situation. A selection of conductors are assumed to be operating at 50 % loadability representing a fairly heavy loading under normal circumstances. The power system, which the conductor is a part of, enters an emergency state where the line must be loaded at maximum capacity for 15 min. The emergency loadability of the line is this case will be dependent on the time period until normalisation, e.g. 15 min, and the loading of the line before the emergency current step, e.g. 50 % current rating. By use of the Cigré guidelines for unsteady state loading of a conductor the results in table 6.21 are reached.

Table 6.21: Emergency operation of selected conductors for a 15 min period with an initial current loading corresponding to 50 % current loading based on Cigré guidelines [102].

Conductor	Current rating at 80/180/210 A	50 % load A	Current to reach maximum emergency operating temperature 15 min. after current step A
ACSR Condor	1000	500	1320
ACSR Martin	1397	699	1995
ACCC 530	1813	907	2110
ACCC 780	2341	1171	2850
ACCC 970	2687	1344	3365
ACCR 824	1797	899	2080
ACCR 1267	2349	1175	2845
ACCR 1334	2429	1215	2965

From table 6.21 it can be seen that compared to the individual conductors current rating, the emergency loading given the initial conditions is approximately 300 A higher the conductors with a diameter close to ACSR Condor and approximately 500 A for the conductors with a diameter corresponding to ACSR Martin. There is thus no difference in the increase in relation to the current rating between the conductors of the same diameter. The step change from the loading under normal operation to the emergency loading does however present some large differences between the ACSR and the composite conductors. Here the composite insulators offer greater current loading as they can operate at much higher temperatures. As long as the composite conductors, e.g. primarily ACCR conductors, are not restricted by sag demands, the emergency operation of these offers much greater current loadings than ACSR conductors.

6.4.2.2 Fault Current Loading

Fault or short circuit currents on overhead lines will lead to increased conductor temperatures. As the fault currents are typically several tens of kA it is necessary to ensure that the conductor temperature is not increased beyond its temperature capabilities. Since fault currents are usually limited to periods below 1 second, a short term conductor temperature of 200 °C is allowed for ACSR conductors. As previously determined in section 5.2.2.2 this temperature limit should also be applied to both ACCC and ACCR conductors.

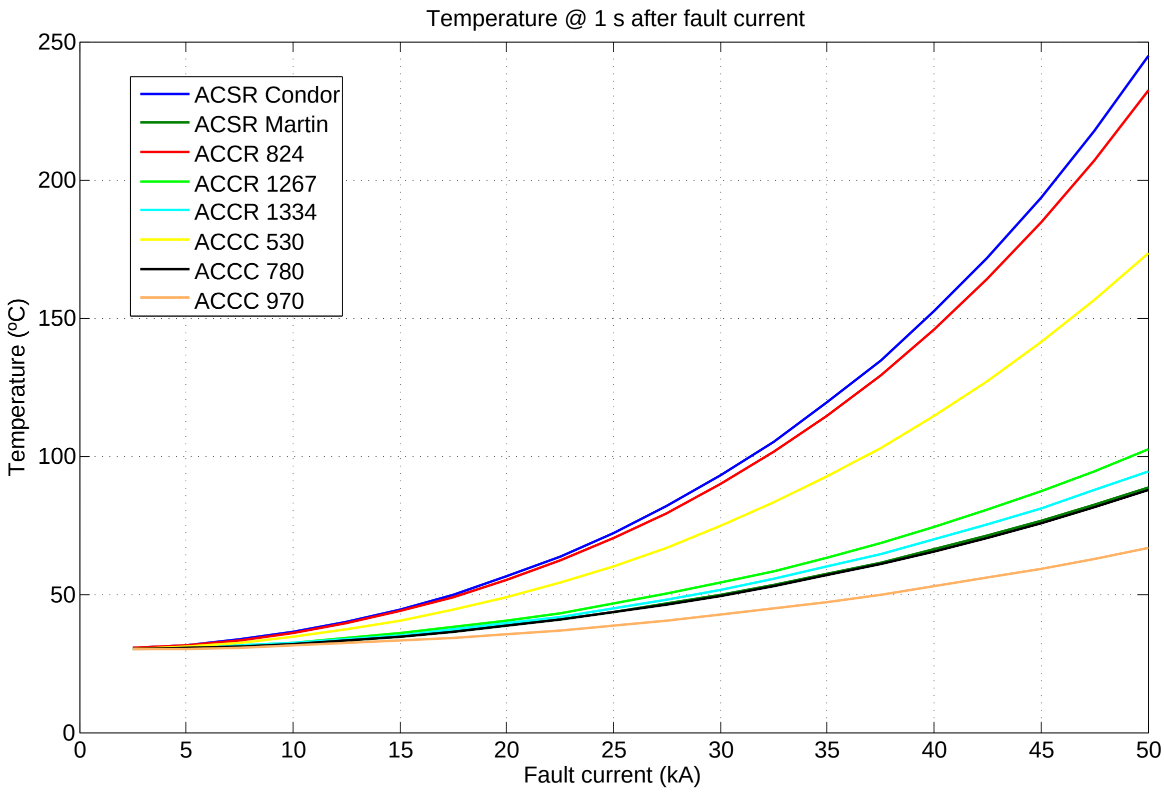


Figure 6.15: Temperature increase of selected conductors dependent fault current applies for 1 second. Based on Cigré guidelines [102].

From figure 6.15 it can be seen that the temperature increase of the composite based conductors is comparable to the temperature increase of ACSR conductors. As mentioned in section 5.2.2.2 it should be noted that composite conductor under normal operation can be at temperatures up to 200 °C (limited to 40 °C in figure 6.15) and thus the temperature of a conductor subjected to a fault current could end up at much higher levels than the recommended 200 °C. How this could affect the integrity of the two different types of composite conductors needs further investigation.

Normally fault currents are limited to periods lower than the 1 second used here. This would mean that conductors of the cross sections used here could handle much higher fault currents than predicted by figure 6.15 all else being equal.

6.4.3 Clearance Requirements for EHV Systems

Based on the clearance demands described in section 6.1.2 and [42] values for general clearance in air for EHV systems are presented. The EHV range goes from 300 kV to 750 kV (system voltage) and besides the minimum and maximum voltages also clearances in air for 400 kV have been included in table 6.22.

Table 6.22: Clearances in air dependent on the highest voltage of equipment for EHV [42].

U_m (kV)	D_{el} (m)	D_{pp} (m)	$D_{50Hz-pe}$ (m)	$D_{50Hz-pp}$ (m)
300	2.10	2.40	0.51	0.83
420	2.80	3.20	0.70	1.17
765	4.90	5.60	1.28	2.30

Notice that clearances will be dependent on correction factors as described in section 6.1.2.

In an actual design process of an overhead line the different correction factors for the clearances should be considered carefully. The clearances given in table 6.22 are based on empirical values for overhead line design [42, 99].

For a 400 kV system these will lead to the estimated clearance demands stated in table 6.23 based on tables 6.1 and 6.2.

Table 6.23: Estimated clearance demands for 400 kV system based on EN50341-3 [42, 99, 115]

Case	Within the span		At the tower		Road surface
	Phase-to-phase (m)	Phase-to-earth (m)	Phase-to-phase (m)	Phase-to-earth (m)	(m)
MDT	3.20	2.80	3.20	2.80	8.80
CS	2.24	1.96	2.24	1.96	8.80
CG	1.17	0.70	1.17	0.70	$5.80 + 1.5 \cdot y_0$

MDT: Maximum design temperature
CS: Conductor swing
CG: Conductor galloping

The values give in table 6.23 can be used to give an estimate of clearances required in a 400 kV overhead line system. Beside the values stated here also insulator connection lengths are to be considered to estimate overhead line geometries. Insulator spacings given in table 4.2 states values between 3 m to 4 m which is in good agreement with required phase-to-earth distances of 3.20 m.

General conclusions are made in section 6.4.4 regarding how clearances will influence the mechanical loading of components in the overhead line system.

6.4.4 Mechanical Loading of Composite Based Insulators and Towers – a Comment

Loading of towers and insulators, as presented in section 6.3, is evaluated based on several different cases and situation that can arise in overhead line systems. When dimensioning both insulators and towers, different load situation affecting the components perpendicular to their lengths (conductor tensions and wind loads), the deflection of the components (post insulators and towers) can be described by equation (6.45). For towers loaded along their length, compromising loads due to conductors, insulators, self-weight and ice loads the loading limit of the tower can be calculated by equation (6.47).

It can be seen that both the deflection and buckling of insulators and towers are dependent on the length of the component. As the voltage levels of overhead line systems are increase, so are the dimensions of insulators and towers to ensure the clearances are kept. At the same the number of conductors supported by the towers and insulators can be increased due to different electrical issues (corona, audible noise and radio noise) thus also increasing the weight that needs to be supported by insulators and towers.

As both lengths and loading are increased with voltage level it thus necessary to strengthen the insulators and towers to ensure the integrity of the system. This can either be done by increasing the stiffness or the dimensions of the components. Stiffness can rarely be increased unless the materials used are replace by stiffer materials, however the dimensions and thereby the area moment of inertia can be increased. For rods the radius is increased (equation (6.48)) while for towers and hollow core insulators both the diameter as well as the materials thickness can strengthen the components (equation (6.49)).

For composite materials this can easily be achieved during the manufacturing. Both pultrusion and filament winding offers great flexibility of altering of the produced components. Limitation might however be imposed due to limits on geometry by the production facilities.

Calculations on dimensions will not be carried out in the present Thesis, as the dimensions are very case specific and dependent on the overall overhead line system design.

Chapter 7

Discussion – a Composite Based Overhead Line System?

In the previous chapters composite materials and components based on composite materials have been presented and discussed. There is still though areas concerning use of composite materials on an extensive basis in overhead line systems that needs to be touched upon. Among these are, if any, the consequence and advantages for power systems of widespread use of composite materials for overhead lines.

Besides this also the composite design ideas presented in chapter 2 must be evaluated based on the material present throughout the present Thesis. Furthermore it is also the intent to answer the question; what can and cannot be done with composite materials in overhead line systems?

7.1 General system considerations for composite based overhead line systems

The consequences to an electrical system by introducing composite materials into the system's overhead line systems have so far not been discussed. The different components have been viewed separately and not as a whole and in interaction with the rest of an EHV AC system. In the following how lightning protection of overhead lines, system stability, line losses and line availability will be discussed.

7.1.1 Earth Wires vs. Surge Arresters

Different means exists for reducing lightning overvoltages on overhead line system including surge arrester, shield or ground wires. Conventionally ground/shield wires have been used to intercept lightning strikes to overhead lines. The ground wires covers the line, making the ground wire the most obvious strike point for lightnings. However some lightning strokes, most likely those of smaller current amplitude, can bypass the ground wire and strike the phase. Ground wires are an effective way of protecting an overhead line system against lightning overvoltages. This is confirmed by lightning transients studies that have been carried out during the PhD . The results are presented in appendix D. For information on transients simulation theory behind the results in appendix D consult appendix C.

The use of ground wires can however present a problem on some overhead line designs, e.g. the Compact Plus Tower in figure 2.3. For the Fibre Tower presented in chapter 2 there is also a problem concerning whether to use ground wires and how they could be connected to earth. Besides the electrical aspects of using earth wires there is though also a question concerning the esthetic impression of the line [9]. Would visual impression of the line be reduced by omitting the ground wires from the design and is sensible with regard to the lightning performance of the line?

An overhead line operating without earth wires or other means of lightning protection will have lightning strikes directly to the phases of the system. Depending on the local lightning intensity this could lead to frequent issues with lightning overvoltages on the line leading to frequent need for clearing of the line. Frequent lightning flashover could also result in electrical ageing of insulators making it necessary in inspect and replace line insulator more often. A line without any kind of lightning protection would thus not seem a suitable solution with the exception of locations with very low lightning occurrences [126, 127].

Thus for the Fibre Tower and for any other towers, it is necessary to protect the overhead line against lightning overvoltages. For the Compact Plus Tower surge arresters are mounted at the top phase ensuring that the voltage of the line will not go beyond the level allowed by the surge arrester. A similar solution could be imagined for some of the designs in chapter 2, for the Fibre Tower a solution based on lightning protection by surge arrester seems unlikely not because of the performance of the line but because also the surge arrester need to be connected to earth. A solution that would be aesthetically pleasing while at the time connecting the surge arrester cannot be imagined [3].

Thus for the Fibre Tower the only solution at present that seems feasible is the use of ground wires mounted at the of the insulating crossarms. For ground wires to an effective protection they must be grounded at regular intervals, in practise meaning at every tower (see appendix D, this also applies for surge arresters). Three apparent solutions for connecting the ground wire to earth can be thought of; 1) through a down-conductor located in the core of the insulating crossarm, 2) by a down-conductor hanging from the ground wire and attached to an earthing rod, 3) through a guy wire support mounted above the phase connected at the tower pole (the pole would need to be elongated) which could also support the insulating crossarm mechanically.

Solution number 2 would not seem acceptable as the area occupied by the tower would have to be expanded to include the area where the down-conductors are grounded. Furthermore a lose hanging down-conductor would be vulnerable to the elements as well as accidental impacts from farming equipment if used in towers crossing fields. Solution 1 and 3 would be possible solutions however these require further analysis if they are to be used. Solution 1 would require that the wall of the insulating crossarms are able to handle phase-to-earth voltage of the system, as the conductor at the surface of the crossarm are at full voltage while the down-conductor would be at zero potential. A large electrical field will be applied to the wall of the insulating crossarm and thus the down-conductor would need to be fully insulated for the phase-to-earth voltage. If and how this is to be achieved would require further investigations. The third solution, grounding the ground wires through use of guy wires supporting the insulating crossarm at the end would require that the tower pole would be elongated beyond the point of connection with the crossarms. This is ensure that adequate air will be present between the down-conductor and the insulator to prevent phase flashover to the guy wire.

No straight forward solution seems apparent with respect to grounding the ground wires on the Fibre Tower presented in figure 2.11 without change of the design.

7.1.2 System Stability

For a transmission line the theoretical steady-state stability limit for the power transmission, P_{max}, along line is given by equation (7.1).

$$P_{max} = \frac{V_{S,pu} \cdot V_{R,pu} SIL}{\sin\left(\frac{2\pi l}{\lambda}\right)} \tag{7.1}$$

Where the $V_{S,pu}$ is the sending end voltage, $V_{R,pu}$ the receiving end voltage, SIL the surge impedance loading (as described below), l the line length and λ the line wavelength. As can be seen from equation (7.1) the steady-state stability limit is dependent on the SIL. In practise the line loading is limited by thermal constraints up to a line length of 100 km. At line lengths above 100 km the line loability can however be expressed as a factor of SIL. The stability limit of a line will go from around 3 SIL at a length of 100 km to 0.5 SIL for very long lines.

Surge impedance load is calculated from $SIL = U^2/Z_C$, where Z_C is the surge impedance of the line and U the system voltage.

$$SIL = \frac{U^2}{Z_C} \tag{7.2}$$

The surge impedance loading SIL is an indicator of the transmission capability of the line as a part of equation 7.1. Loading over the surge impedance load can result in severe line instability [128].

The SIL is affected by the system voltage which should be increased to increase the transmission capability of the line. This is to a certain extent not dependent on whether or not composite based components are used since composite insulators are available for a wide voltage range up to at least 765 kV as a standard component.

The other factor affecting the transmission capability with regard to stability is the surge impedance of the line. The surge impedance is dependent on the inductance and capacity of the line and is calculated as the square root of impedance over the capacity of the line.

$$Z_C = \sqrt{\frac{L}{C}} = \sqrt{X_L \cdot X_C} \tag{7.3}$$

Whether or not the use of composite materials affect the surge impedance of the line is then a question of whether or not the inductance and capacitance of the line is dependent on the materials used in the system.

Inductances and capacitances of a line are not directly dependent on the materials used for the overhead system. They are instead dependent on the line geometry as can be seen from equations (7.4) and (7.5). The three prime parameters are the mean geometric phase-to-phase distance, D_M, the equivalent conductor bundle radius, r_B, and the mean conductor height above ground, h_M. Besides these the inductance and capacitance of the line are dependent on the magnetic field constant, μ_0, the conductor length, L, the number of subconductors, n_2, and the dielectric constant, ε_0.

$$L = \frac{\mu_0 \cdot L}{2\pi} \left(\ln \frac{D_M}{r_B} + \frac{1}{4n_2} \right) \tag{7.4}$$

$$C = \frac{2\pi\varepsilon_0 \ln \frac{2h_M}{D_M}}{3 \ln \frac{D_M}{r_B} \cdot \ln \frac{2h_M}{\sqrt[3]{r_B \cdot {D_M}^2}}} \tag{7.5}$$

Equation (7.4) is the positive sequence inductance of a fully transposed three phase transmission line and equation (7.5) the capacitance of a single circuit for a line without earth conductors. They do thus not describe all lines nor the full inductance or capacitance of a line but they are however representative for which factors the inductance and capacitance of a line are dependent on [42, 128].

The surge impedance of an overhead line is thus not directly dependent on the materials used in the components of the line. However it is dependent of the geometry of the line where the use of composite materials may result in differences compared to conventional ways of construction. It is however difficult to predict the direct impact of using composite materials.

Generally it applies that the surge impedance of the line can be reduced by reducing phase spacing (reduction of D_M), increasing the numbers of subconductors (increasing n_2), increasing conductor radius or increasing the bundle radius (and thereby r_B in both cases).

The effect of making these changes will not be directly examined here as it is not directly related to the widespread use of composite materials in overhead line systems.

The conclusion is that the use of composite based conductors compared to a conventional system of the same geometry will not affect the SIL of the system. The use of composite components could however result in changes on the overhead line geometry and thereby lead to change in the SIL of the system as both increases and reductions. The expectations are however the relatively large changes of the line geometries are needed to have a significant affect on the SIL of system.

7.1.3 Line Losses

In table 4.4 the DC resistance of the different conductors are given. Comparison of the resistances shows that with respect to line loses the ACSR and ACCR conductors are very similar. Thus the only difference with respect to line losses between these two conductors is that the ACCR conductor is able to operate at higher temperatures where the losses in the line though will be higher.

The ACCC and ACCR-TW do show lower DC resistance than the ACSR and ACCR conductors. This is due to their increased amount of aluminium per cross section. These conductors could, if replacing ACSR conductors and operating at the same temperature, reduce the lines losses on a line. Of the two conductor types, the ACCC offers the most aluminium per cross section and this conductor therefore also has the lowest resistive losses.

Loss calculation will not be presented here. It should however be considered by line owners whether replace of conductors with a TW strung conductor is economically and environmentally favourable. The ACCC conductor could, all else being equal, cut losses with 25 %.

7.1.4 Line Availability

An aspect of overhead lines that demands a lot of attention in today's power system, is the time components are available for operation in the power system. It is not easy to draw specific conclusions on whether or not composite materials in overhead lines will affect the availability of lines. It is though the author's impression that the use composite materials in overhead line systems should not affect the line availability. This is based on that much experience have been made with composite materials over the last decades and for composite insulators data on in-service performance have shown that the failure rate of composite insulators are now comparable to the failure rate of conventional glass cap-and-pin insulators (see section 5.1.6.2). For towers, which are purely mechanically loaded, much experience have been made in the construction industry. As long as recommended practices are followed composite towers would not either seem to be caused for reduce availability of overhead line systems. With composite conductors the experience is still very limited both with regard to in-service performance over time as well as the amount of conductors in-service.

7.2 Composite Overhead Line Designs

In the following section the different design ideas presented in chapter 2 are discussed in relation to the previous chapters.

In general it can be stated that the use of composite based conductors can be done for all the design ideas. For each final design however sag-tension and sag-temperature must however be carried out.

With regard to insulators it should be noted that guidelines and recommendations state that at 400 kV, corona rings should be used at both ends of the insulators, see table 5.1.

7.2.1 I-pole Without Crossarms

In figures 2.7 and 2.8 designs based on a composite I-pole with either post insulators or braced line post insulators supporting the conductors of the phase conductors. This system would need a pole with a height of at least 24 to 28 metres (rough estimate) depending on the use of insulators. Poles at these height are commercially available in North America, as can be seen from table 4.6. Information on at which voltage levels these towers have been applied have not been directly obtained. Other manufacturers have supplied tower up to applied at up to 115 kV. The concern is whether or not these towers can comply with the loadings required for at EHV.

With regard to the use of post insulators it should be noted that the post insulators listed in table 5.2 do not allow sufficient cantilever load for them to be used post insulators at

EHV as below 10 kN is stated as the maximum load. The vertical cantilever load on a post insulator applied for 400 kV are roughly estimate at around 83 kN for a three conductor bundle with ice load while a value of 75 kN is estimated for torsional loads. Bracing of the line post insulator will make it possible for the line post insulator to handle the design loads as line post in this situation will be in compression and the suspension insulator in tension. Suspension insulators are available at tensile strength up to 300 kN and should therefore not represent a problem. If line post insulators are to be used alone this will most likely have be developed for the project.

Depending on the limitations to mechanical loads to towers, the two designs could be realised with a relatively short time – 2-3 years. Composite conductors are fully available as are the braced post insulators. However the I-pole design with unbraced line post insulators needs some further investigations, though similar designs with composite post insulators are already in-service.

The designs can carry one or two ground wires, which can be mounted at the top of the pole. A down conductor can either be mounted on the outside or inside of the pole depending on preferences.

7.2.2 Y-tower

The Y-tower equipped either with V-suspension insulator sets or a single suspension insulator per phase are depicted in figures 2.9 and 2.10. A rough estimate of the tower height based on 9 metre sag and a minimum of 9 metres clearance is 23-25 metre at the connection with the tower arms. How the arms should be attached to the tower can not be satisfyingly estimated here. A rough estimate on the length of the tower's arms are 11-15 metre dependent on the insulators used. A V-string will allow greater compaction of the conductors and thus requires shorter crossarms. The connection point between the crossarms and body needs to be able to handle very large bending moments. This could lead to large dimension of the arms and thus increase the visual impact of the design. This requires further investigation to be fully evaluated.

Since composite suspension insulators are intended for supporting the conductors there should be no unknown mechanical or electrical issues with the insulation as both requirements can be fulfilled by the high load suspension insulators listed in table 5.2 as examples.

The main factors determining the time frame for implementation of this design are the crossarms and the tower. The mechanical dimensioning of the crossarms and tower body must be carried out and it must be determined whether or not the required dimension can be met by current production facilities. An estimate for development of the arms and tower including tests on prototypes would be 3-5 years.

Ground wires can be mounted at the at ends of tower arms giving a good coverage of the conductors. The ground wires can be connected to ground through a down conductor either mounted inside the tower arm and body or running along the exterior of the tower.

7.2.3 Y-tower with Insulating Crossarms

The Fibre Tower or Y-tower with insulating crossarms is shown in figure 2.11. A rough estimate for dimensions follow the Y-tower design with V-strings described in the previous section. Since suspension insulators are not used in the design and the crossarms in themselves are insulating for the current design the tower height is estimate lower at around 20 metre. As with the design above the bending moments and loads on the crossarms are larger which could lead to a bulky design of the arms and the connection point between the arms and the tower body.

As the insulators are the insulating crossarms in this design, let it be stressed here that these specially designed crossarms will need to follow IEC60071 and EN50341 with respect to demands for lightning and switching overvoltages as well as IEC60815 with respect to creepage distances. The creepage distance can possibly be lowered one pollution class as have been observed for apparatus insulators in section 5.1.2.2. This would however require careful consideration.

With regard to the mechanical properties of the design, it should be noted that since the crossarms are insulator, the expected mechanical stress in the crossarms may not be larger than half the actual mechanical stress limit of the crossarm, since a material partial factor of $\gamma_M = 2$ must be used according to EN50341. The mechanical stress should furthermore be limited in the crossarms to ensure that voids do not arise between the rubber sheath and the composite core. The mechanical demands will most likely lead to crossarms greater in diameter than for the Y-tower with suspension insulators.

Extensive testing should be carried out for the design of the insulating crossarms for this design and the lightning protection of the system should be further considered as this will have great importance for the final crossarm design. How to protect this design from lightning overvoltages is discussed separately in section 7.1.1. It would be prudent to consult hallow core insulator manufacturers for the design of the crossarms. This design due to the long crossarms and the need for electrical insulation, puts high demands on the mechanical strength of the crossarms and tower and a the same time the electrical integrity of the crossarms must not be compromised. The tower pole would need development with regard to mechanical dimensioning and design of the joints between the tower and the crossarms. The time frame for the development of the design could be anywhere from four to seven years, if not more.

7.3 What do Composite Materials Based Components Offer?

In general it should be noted that due to the manufacturing processes of components in composite materials being complex processes, the complexity of composite based components is naturally limited. This results in that composite based component are simple geometrical objects which is in agreement with the design principles found in section 2.1.2.

In the following, possibilities, limitations and risks identified through this Thesis is summarised and listed for insulators, conductors and towers respectively.

7.3.1 Insulators

Composite insulators are very complex components, which offer among other things better pollution performance than glass and porcelain insulators. In the following the advantages, limitations and risks related to composite insulators are discussed in short.

7.3.1.1 Possibilities

Composite insulators, especially silicone insulators, offer better pollution performance than glass and porcelain insulators. This is due to the housing of composite insulators being hydrophobic. For silicone rubber housing this is a permanent effect. Though composite insulator exhibits better pollution performance, the same creepage distance demands as for glass and porcelain are applied. Suggestions for lower the creepage classes for silicone apparatus insulators have been made in [87]. This could perhaps be applied for the Fibre Tower design idea. Consult section 5.1.2.2 for more information on the pollution performance of composite insulators.

Composite suspension insulators are available at voltage levels up to 765 kV as standard components and thus cover the EHV range. Compared to glass and and porcelain insulators, composite insulators have favourable weight, slimmer profiles and are based on materials of greater strengths. Several different types of composite insulators are available, making it possible to apply insulators and insulator sets in many different configuration. By use of this, it is possible to have the insulators make up the crossarms to the tower body. Composite suspension insulators are available for tension loads as high as 300 kN (see section 4.1.1.3).

Composite insulators offers failure rates comparable to glass insulators, as discussed in section 5.1.6.2.

7.3.1.2 Limitations

According to IEEE recommendation, corona rings must be applied at both ends for insulators in EHV systems. This should be noted when designing EHV overhead line systems (see table 5.1).

For the Fibre Tower design idea the corona rings for control of the electrical field have not been considered. To ensure an acceptable performance of Fibre Tower with regard to electrical ageing the use electric field control should be considered.

For the commercially available composite post insulator it was noted that the cantilever load was limited to below 10 kN. For transmission line systems this is far from enough compared to the weight of the conductors bundles. Unless higher cantilever loads of commercially available composite post insulator are allowed, it would only be possible to used these post insulator in braced configurations. It would however be possible to use specially designed post insulators or hollow insulators as insulating crossarms.

7.3.1.3 Potential Risks

The electrical and mechanical ageing of composite insulators are very dependent upon the design and quality of the composite insulators. It is therefore necessary that manufacturer use adequate levels of quality control and use the most current insulators designs as recommended in [62, 69, 76, 129] (see also section 5.1).

Further to prevent mechanical and electrical ageing mechanisms like water ingress, brittle fractures and corona corrosion of the core, it is paramount that the housing and end fittings seals remain intact throughout the insulators service time. Part of ensuring this is correct handling of insulators as well ensuring mechanical loads do not increase beyond the insulators capabilities (see section 5.1).

Composite insulators are, unlike glass insulators, difficult to inspect with regard to damages to insulators unless severe. End fitting seal failures and housing damage can rarely be seen with the naked eye. Several inspection methods have been developed for composite insulators. These are however often reliable on both heavy equipment and experienced inspectors to be effective. There is a risk of assumed healthy composite insulators failing either mechanically or electrically (see section 5.1.6.4).

Insulators are flammable which should be considered for overhead lines passing woods and farmland. Here the possibility of destruction of the insulators should be considered (see section 5.1.5.3).

Composite insulators are vulnerable to attacks by birds and rodents. This will lead to reduction of the electrical strength of attacked insulators, as well as result in core exposure initiating several other failure mechanisms. It should be noted that bird attacks have only been observed in a limited number of cases and usually where larger birds are present. During storage of composite insulators, rodents should not have access to the insulators.

These damages are normally clearly visible (see section 5.1.5.5).

7.3.2 Conductors

Composite conductors offer great advantages with regard to sag development under temperature increase. There are however, also limitations in their ability to reduce sags as well as risks with regard to the integrity of the conductors. These findings are summarised in the following sections.

7.3.2.1 Possibilities

The possibilities or advantages that composite based conductors offer, are their low sag development with temperature and their high temperature capabilities. The ACCC and ACCR conductors are, dependent on tensions applied, capable of carrying greater currents at the same sag as seen in section 6.4.1.3. This capability is however not unique to the ACCC and ACCR conductors as mentioned previously. It should though be mentioned that very low sag development of the ACCC conductor compared to other conductors it in a league of its own.

7.3.2.2 Limitations

One of the main limitations with composite based overhead line conductors are their price. As previously stated both the ACCC and ACCR conductors are more expensive than ACSR conductors of the same diameter.

Both conductors shows good sag-temperature curves compared with ACSR conductor with the ACCC conductor outperforming the ACCR conductor. In spite of the conductors' good sag-temperature profiles neither of them give rise to any remarkable conductor sag reduction when ice loads on the conductors are considered. Compared to ACSR conductors of the same diameter, ACCC and ACCR conductor do not give rise to any noticeable compaction of overhead line systems as shown in section 6.4.1.1.

A comparison of the ACCC and ACCR conductors' characteristics in tables 4.3 and 4.4 with the ACSR conductors do not however offer any other clear advantages besides the cores' lower thermal expansions and slightly better effective elasticity modulus.

7.3.2.3 Potential Risks

The potential risks of using composite overhead line conductors could seem like many in relation to section 5.2. Most of the issues brought forward in section 5.2 are also present on conventional ACSR conductor as well as all types of overhead line conductors. Thus conductor damage due to lightning termination, birdcaging and cyclic fatigue are failure mechanisms present on all conductors types.

The potential risks or the new failure mechanism introduced with composite conductors are few but very different in nature compared to ACSR conductors.

For the ACCR conductor, the conductor apparently most similar to ACSR conductors, brings with it a suspicion of the potential development of micro cracks in the conductor core under cyclic loads. Test carried out by the manufacture as reported in 5.2 do not show any indications of this being an actual issue for the conductor. However test are limited as are the in-service experience with ACCR conductors. For the moment though micro cracks development leading to mechanical ageing under cyclic loads should not be considered as major risks nor as a disadvantage compared to ACSR conductor for the moment being.

For the ACCC conductor three issues could be listed as potential risks. These are the possibility of bending fracture of the core and the thermal sensitivity of the core with respect to mechanical ageing. Furthermore also the UV sensitivity and corrosion sensitivity of the core represents a new issue in relation to overhead line conductors. The later of these, the UV and corrosion sensitivity of the core, is a time – as well as exposure intensity dependent – failure mechanism. Under normal circumstances the core will not be exposed to sun light, acids or corona. This in combination with the manufacturer's tests on the sun light resistance and brittle fracture resistance of the core as presented in section 5.2 shows that ageing due to sun light and corrosion does not pose any noticeable risks with respect to the integrity of conductor. This is though dependent on reoccurring visual inspection of the line where exposure of the core can be detected. Replacement of the exposed section of the conductor should be carried out.

The temperature and bending sensitivity of the core does however represent potential risks that could lead to failure of an ACCC conductor. The issues with these degradation mechanisms are that they cannot be detected while the conductor is in-service as the core is fully surrounded by aluminium. Core fracture due to excessive bending of the core during installation can be prevented by adopting correct installation practice and keeping minimum limits to the bending of the conductor. But does excessive bending occur it is not possible to detect before the conductor have failed in-service and this should be considered as a risk when using ACCC conductors. The temperature sensitivity of the core must also be seen as a potential risk. The core will mechanical age if exposed to temperatures slightly lower and well above 200 °C. Thus if the conductor is run at its maximum allowable temperature at 180 °C mechanical ageing can take place and the risk of this is increased of local hot spots exists along the length of the conductor. This ageing mechanism is hard to predict in-service and no methods of detection is present in the literature.

With regard to clearance dimensioning it should be noted that in contrast to the recommendations in EN50341-1 [99] the Danish NNA in EN50341-3 does not state ice load as as electrical clearance load case. This could lead to situation with composite based conductor, especially the ACCC conductor, where clearance are not based on actual sags.

7.3.3 Towers

The possibilities, limitations and risks identified with composite towers throughout this Thesis are summarised in the sections below. These are primarily based on towers in fibreglass materials.

7.3.3.1 Possibilities

A major possibility or advantage of composite based overhead lines is worth mentioning here. This is the possibility of tailoring composite towers to the geometries needed to meet the loads, which composite towers are subjected to in-service. Thus depending on manufacturing method it is possible to continuously alter wall thickness, cross section geometry and tower lengths given the possibility of manufacturing towers specially tailored for a chosen application (see section 3.2).

The life expectancy of composite towers is fairly long, if a mean life expectancy can be considered as 50 years for overhead line components. From table 4.6 it can be seen that life expectancies is up to 80 years dependent on the manufacturer.

7.3.3.2 Limitations

A clear limitation with composite towers at present is the limited number of manufactures especially in Europe but also to a degree in North America as mentioned in section 4.1.3.2. With regard to fibreglass composite towers no manufacturers with composite towers as a “standard” product have been found in Europe. The production capabilities should though be present in the EU.

For application requiring lengths at above 30-40 m there could be a limitation with regard to composite towers since they are limited in length by the production facilities. One manufacturer is making use of module towers in an attempt to overcome the length limitation imposed in the manufacturing. Furthermore there is also a limit in achievable diameter of composite towers. It is not expected that composite tower for EHV level or at least 400 kV however will reach the limit in diameter. Lengths could be an issue for slim profile designs of towers.

Compared to steel towers, greater care should be taken with composite towers with respect to joining and assembly. Recommendations with geometry of joints and applications of adhesives should be followed (see more in section 3.4).

7.3.3.3 Potential Risks

Compared to steel towers, which are commonly used at EHV levels, the only issue with composite towers to be perceived as a risk, are composite towers' fire resistance. Though composite based towers can be treated with fire retardants, the epoxy matrix is a flammable material and thus dependent on the exposure composite towers could perish in large fires. It should be noted that no reports of this have been found in the available literature (see section 5.3.5.5 for more information).

7.3.4 Further considerations

In the following subsection further possibilities and limitations of composite components are mentioned.

7.3.4.1 Added Critical Flashover Voltage of Composite Towers

An issue with composite overhead line poles not discussed until now is that fibreglass poles will increase the critical flashover voltage (CFO) for insulators mounted on the pole. This happens since the pole in non-conductive and is able to resist some level of lightning overvoltages. In [130] a short fibreglass pole is tested with respect to added CFO of the insulator due to the fibreglass tower. It concluded that fibreglass tower offer greater increase of the CFO in combination with an insulator than wood. This ability has primarily been used at distribution level but could perhaps also improved the lightning of transmission line systems by added CFO.

Besides tests on the CFO added by fibreglass pole to insulators also ageing test were carried out on fibreglass tests subjects for the ageing of the withstand strength. The ageing test in general showed slow ageing of the fibreglass test subject with the exception of a salt-fog exposure under an electrical stress of approximately 80 kV/m which severely degrade the impulse strength of the fibreglass [130]. It should be noted that the test are made with intention of application at distribution level. This could though perhaps also be exploited at transmission levels.

7.3.4.2 Costs of Composite Components

Costs of composite materials have not been given much attention in the previous chapters. A comment on this topic should however be made. Costs of composite components are very dependable on the materials used for the components as well as the intended use. For the application in components of overhead lines often well known materials are used. For composite insulators a core rod of fibreglass is used. Despite of the very knowledge intensive process behind the manufacturing of composite suspension insulators reports have been made that the price of these is comparable to the price of conventional insulators for suspension application. Information on the costs of post insulators have not been available.

For composite towers the costs are unknown and no information on European suppliers of standard composite towers have been found. It must be expected that the costs of composite based is higher compared to steel towers.

Composite based conductors are more expensive than their ACSR counterparts. For the ACCC conductor costs of around two and a half time the costs for ACSR conductors have been made. ACCR conductors would seem to be higher still in price with a factor of ten compared to ACSR conductors. Composite conductors are today almost exclusively applied to the uprating of older lines where costs of the composite conductors can be justified compared the price of building a new line in place of the old one [45].

7.3.4.3 Recycling of Composites

The industry for recycling of composite materials is at the moment not fully developed. It is though expected that as the first generation of wind turbines age and must be replaced that recycling of composite materials will develop further.

In general composite materials can be recycled. How and to what is however dependent on the composite material itself. In example, can thermoset based composite materials be used as an energy source by burning, use of pyrolysis to extract polyesters from fibreglass whereby the polyesters can be used in new products while the glass fibres can be used for mats or composite materials can be granulated and used as fillers or reinforcement [55, 131].

7.4 Future Research Areas

During the PhD project and in the present Thesis several topics have been found which deserves further research efforts.

First of all, there is the Fibre Tower which Energinet.dk is currently carrying out research on. For the Fibre Tower several different research areas related to the application of composite materials in overhead lines an be listed. Thus to work towards the Fibre Tower solution, research on the electrical dimensioning, including electrical field control, for the insulating crossarms should be carried out. In relation to this, how the earthing system of the tower should be designed, including the possibility of a conductor in the core of the insulating crossarm, needs further consideration.

Besides the electrical aspects of the Fibre Tower design also the mechanical joining of the crossarms to the tower body, as well as the mechanical dimensioning of the arms and body, should be further researched.

In relation to both the Fibre Tower design, but also fibreglass composite poles and towers in general, research concerning the added critical flashover voltage of insulators should be carried for voltages at transmission levels. It should further be evaluated to what extent the added critical flashover voltage of a fibreglass composite tower contributes to the reduction of the lightning failure rate of a transmission line.

A general concern with all composite materials based on organic compounds which have not been answered in the present Thesis, is to what extent, fire could be a problem with respect to the integrity of composite based overhead line system and the individual composite based components.

Composite insulators can be subjected to failure mechanisms that are difficult, if not impossible, to detect by visual inspection of overhead lines. Some methods of inspections have at present been developed but further research on and development of inspection methods for composite insulators still needs to carried out.

For composite based conductors it could be fruitful to find alternatives to the composite materials used for the conductor cores today. Besides alternatives to the ACCC and ACCR cores, also failure mechanism for the two conductors could deserve more attention. For the ACCC conductor the temperature stability of the core close to maximum operating temperature and consequences of potential hot spots on the conductor would benefit from more knowledge. For the ACCR core further research into the possibilities of development of micro cracks in the material under loads present in overhead line systems if of interest.

Chapter 8

Conclusion

8.1 Line Designs

Several overhead line designs from design project to actual applications have been presented. Based on these solutions designs steps for reducing the environmental impact, with emphasis on the aesthetics, for overhead lines have been outlined. The established design steps are:

- Use of pole towers instead of lattice towers
- Application of insulators as crossarms
- Compaction of phase spacing
- Removal of ground wires

Based on the design steps, tower designs intended based on composite materials were presented. Amongst the designs are the Fibre Tower, a tower design intended to use insulating composite materials for the tower body and crossarms.

Dimensioning guidelines for composite components and overhead line system geometries have been outlined. This includes clearances for overhead lines, sag-tension-current relations for conductors along with tension limits and loading cases for towers and insulators.

8.2 Composite Based Components

The three main components of overhead lines systems are all available based, in varying degrees, on composite materials and for application at EHV levels.

Insulators are available based on a core rod in composite materials – special glass fibres embedded in an epoxy – covered by a rubber housing and with metal end fittings. The service experience with composite insulators stretches over several decades and is considered to be a good alternative to conventional insulators for a multitude of applications.

Composite based overhead lines have only been available for approximately teen years and the service experience with these are therefore limited. Composite conductors are based on a composite material core covered with aluminium strands in which the current is conducted. Presently two different types of composite materials are used for the cores of the two different conductors that are commercially available; the ACCC conductor's core is based on glass and carbon fibres imbedded in an epoxy, while the ACCR conductor's core consists of aluminium oxide fibres imbedded in aluminium. The ACCC conductor shows the greatest reduction in sag as a function of temperature compared to ACSR conductors, the ACCC conductors is though at the same time the conductor type evaluated to include the greatest risks in application of the two conductors.

Towers based on composite materials have only rarely been used at transmission levels and predominantly in North America at distribution levels. The main limitation with composite towers is the production capabilities in relation to the required lengths and thicknesses of the towers to handle the mechanical loads that can arise as well as ensure adequate clearance to ground. Commercially available towers are typically constructed from glass fibre mats and long fibres imbedded in either polyurethane or vinylester. Also towers based on concrete reinforced with carbon fibre composite rods have been applied for towers in overhead line systems.

Composite based components have been reviewed with respect to the different ageing mechanisms that the components can be subjected to in-service. Several ageing mechanisms can be identified, most of these can be limited effectively by a combination of quality of the manufactured components, design of the components and overhead line system and correct handling of components during installation and transportation.

8.3 Possibilities, Limitations and Risks

The content of the present Thesis is a reference for design of overhead transmission line based on composite materials. Dimensioning guidelines, design suggestions and ageing mechanisms, which need to be considered when dimensioning overhead lines based on composite materials have been out lined in chapters 2, 5, 6 and 7.

The following possibilities, limitations and risks have been identified with respect to application of composite materials in overhead lines compared to conventional components.

Insulators

Possibilities: Composite insulators, especially with silicone housing, show better pollution performance and can therefore be applied to reduce flashovers related to pollution. Composite insulators have slim profiles and are available at all voltage levels in the EHV range in the same tensile strength classes as glass insulators. Composite insulators can be used both under compression and tensile loads giving great flexibility with regard to crossarm configurations based on insulators. The failure rate (inability to support mechanical or power frequency voltage loads) is comparable to glass insulators.

Limitations: For composite insulators at EHV levels corona rings must be applied to the insulator ends to control the electrical field and prevent corona related deterioration of end fitting seals and housing near the end fittings. The commercially available post insulators presented in the Thesis shows very little ability to handle cantilever loads and these can only be used if braced. Specially designed insulators should however be able to handle the cantilever loads in the insulators configuration presented under the design ideas.

Risks: The performance of composite insulators is very dependent on good manufacturing quality as defects can quickly give rise to acceleration of ageing mechanisms on composite insulators. Furthermore the housing and end fittings seals must remain intact throughout the insulator's service life. Composite insulators have been observed as being subject of bird attack in some countries and are vulnerable to direct exposure to fire. Several of the ageing mechanisms affecting composite insulators are difficult to detect during inspections and special inspections techniques must be adapted.

Conductors

Possibilities: Composite based conductors have slower sag development with temperature than ACSR conductor, especially the ACCC conductor, and composite conductors can tolerate higher temperatures than ACSR. Thus it is possible for composite conductors of the same diameter as an ACSR conductor to carry larger currents and thus power at the same sag as the ACSR conductor. How much is though dependent on installation tensions. Due to the higher temperature limits of composite conductors, they also offer greater current loadability during emergency loadings.

Limitations: Though composite conductors show good sag-temperature relations, they do not offer much reduction in the sag with relation to clearances. This is because ice loads on the conductors will approach the sag of ACSR conductors. For a 300 m span, dependent on tension levels, the sag of composite conductors compared to ACSR conductors of the same diameter is reduced approximately one metre.

Risks: Only the core of the composite conductors represent new risks compared to conventional ACSR conductors. For the ACCR conductor there could be an issue with development of micro cracks in the core leading to mechanical ageing. Tests have not been able to show this issue developing for overhead line application. However since the service experience is limited, it cannot be concluded that micro cracks do not present a potential unexpected mechanical ageing. For the ACCC conductor two issues are of concern; if the conductor is subjected to excessive bending the core will fracture which will lead to in-service mechanical failure and the core sensitive to temperatures close to the maximum operating temperatures established by the manufacture. No ways of inspecting if these issues are under development have been presented by the manufacture.

Towers

It should be noted that the following conclusions are primarily based on composite towers based on fibreglass materials.

Possibilities: Tailoring of composite towers geometries (wall thickness and diameter) can be tailored to a great extent, thus making it possible to design the tower for the actual loads expected. Furthermore the life expectancy of composite based towers is favourable with estimates on up to 80 years.

Limitations: Presently there are a very limited number of manufacturers with composite towers as a standard product and these are primarily based in the US. Production lengths of composite towers could also prove to be a limitation. Currently production lengths of 30-40 metres are commercially available which could prove too little with regard to clearance to ground. The loadability of the commercially available towers has not been examined.

Risks: Composite towers can be treated with fire retardants to increase the resistance to fire. However composite towers potential vulnerability to fire must be further investigated before final conclusions can be drawn on this subject.

8.4 System Aspects

Lightning protection: Several of the design ideas presented in the Thesis were suggested as being constructed without lightning protective measures. In relation to this, it was concluded that overhead lines must be equipped with lightning protection either in the form of ground wires or surge arresters. Both solutions requires a connection to earth to be effective which must be considered in relation to insulating composite materials used for the tower body, especially in the case of the Fibre Tower, as earthing represents a challenge in this design.

Line parameters and system stability: Composite materials' influence on line parameters and system stability have been examined. The conclusion of the examinations are that the use of composite materials in overhead lines will not directly affect the resistance, capacitance or inductance of an overhead line. Compaction as a result of application of composite materials will only marginally affect line parameters and the system stability limit of overhead lines.

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Appendix A

Strain Tension in Overhead Conductors Model

The STOC method was presented in [125] and was intended to be applicable to all conductor types including gap-type conductors, where the aluminium does not contribute to the strength of the conductor. The model will be explained in the following sections.

Reference Lengths

The STOC method makes use of reference lengths for both the core and the aluminium layers around the core. For conductors were both the aluminium and core carries a part of the load the reference lengths will be the same for core and aluminium since they will be clamped together at the ends. For conductors of the gap-type or with annealed aluminium the reference lengths will not necessarily be the same.

The reference lengths for the aluminium layer, $L_{0,A}$, and for the core, $L_{0,C}$ are based on the geometrical length of the conductor, L, and the following elongations, ε, of the two conductor components; tension, H, temperature, θ, and creep.

$$L_{0,A} = \frac{L}{1 + \varepsilon_{H,A} + \varepsilon_{\theta,A} + \varepsilon_{Creep,A}} \tag{A.1}$$

$$L_{0,C} = \frac{L}{1 + \varepsilon_{H,C} + \varepsilon_{\theta,C} + \varepsilon_{Creep,C}} \tag{A.2}$$

Elastic Elongation

Elastic elongation, ε, is described by well known equation for mechanical elongation. The equation is applied separately to the aluminium layer and the core and is dependent on tension, H, elastic modulus, E, and cross section, A.

$$\varepsilon = \frac{H}{E \cdot A} \tag{A.3}$$

Thermal Elongation

The thermal elongation calculations are based on thermal expansion of the aluminium and core. The thermal elongations of the core and aluminium are calculated individually and will be equal at the installed temperature but differ in all other situations. Internal stresses in the conductor are a result of this. The thermal elongations are calculated based on the thermal expansion coefficient, α, and the temperature difference between the current and reference state, ΔT.

Creep

Two kinds of creep are modelled in the STOC method. These are metallurgical, ε_{mc}, and creep due to high loads, ε_{gs}.

$$\varepsilon_{Creep} = \varepsilon_{mc} + \varepsilon_{gs} \tag{A.4}$$

Creep due to high loading is only dependent on the line construction and the maximum loading experience in service. The amount of creep can be determined from the stress-strain curves of the conductor.

Metallurgical creep follows the equation (A.5). The metallurgical creep is dependent upon the constant coefficients K, Φ, β and μ. These coefficients are determined experimentally. The variables are temperature, θ, stress, σ, and time, t.

$$\varepsilon_{mc} = K \cdot e^{\Phi\theta} \cdot \sigma^{\beta} \cdot t^{\mu} \tag{A.5}$$

Performing the Sag-Tension Calculation

The STOC method is a variation of the strain-summation method often used for sag-tension calculations. The STOC method algorithm calculates the conductor behaviour (core and aluminium elongation) independently from the span geometry – the sag of the conductor based on tension, span length and conductor weight.

The aluminium tension, T_A, is calculated based on the core length, which is equal to the aluminium length, L_A. The total conductor tension, T_{Cond}, is equal to the sum of the tension in the core, T_C, and the aluminium, T_A. Based on the conductor tension the conductor length, L, can be calculated based on span geometry. The conductor length, L, is compared to the core length, L_C, and the core tension, T_C, is iterated upon until the difference between L_C and L is below a certain value (usually 0.00001 %).

The process of calculating aluminium tension is, firstly calculation of the aluminium elongation, ε_A based on the length of the core, $L_A = L_C$, and the reference length of the aluminium, $L_{0,A}$.

$$\varepsilon_A = \frac{L_A}{L_{0,A}} - 1 \tag{A.6}$$

Next the elongation of the aluminium due to tension, $\varepsilon_{T,A}$, in the conductors is calculated by subtracting the elongation of the aluminium due to thermal expansion and creep, $\varepsilon_{\theta,A}$ and $\varepsilon_{Creep,A}$ respectively, from the total elongation of the aluminium, ε_A.

$$\varepsilon_{T,A} = \varepsilon_A - \varepsilon_{\theta,A} - \varepsilon_{Creep,A} \tag{A.7}$$

Based on elongation due to tension, $\varepsilon_{T,A}$, the elastic modulus of the aluminium, E_A, and the aluminium cross section, A_A, the tension in the aluminium, T_A, can be calculated.

$$T_A = \varepsilon_{T,A} \cdot E_A \cdot A_A \tag{A.8}$$

The entire STOC algorithm is depicted in figure A.1.

[125]

In the case that the tension in the aluminium goes below zero due to the thermal elongation of the aluminium in relation to the core, the aluminium goes slack and the core carries the entire mechanical load. The point at which the aluminium goes slack is also known as the knee-point temperature. The tension in the aluminium will at minimum be zero or a small negative value (around 10-20 MPa) of compression in the aluminium is allowed [125].

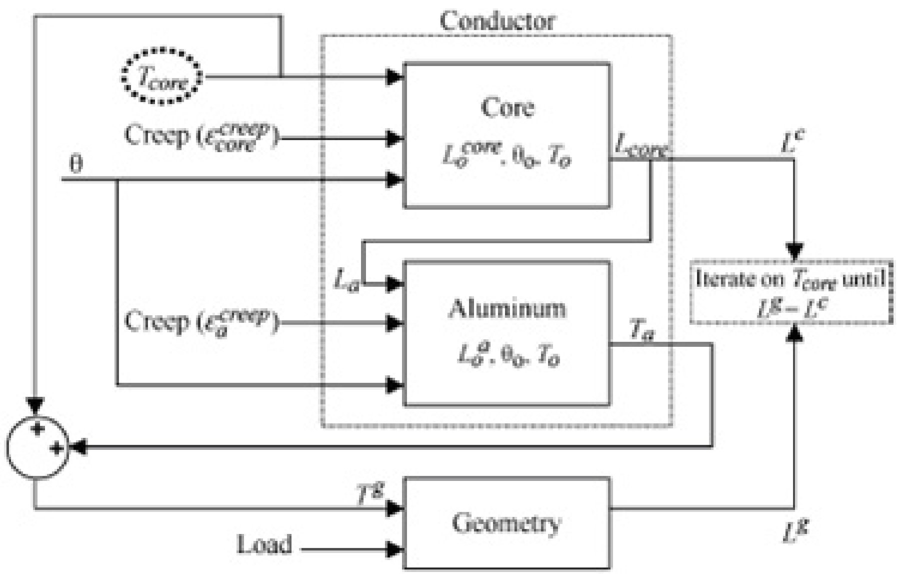

Fig. 15. Iterative process of the STOC sag-tension calculation method.

Figure A.1: Layout of the iterative process of the STOC method [125].

Appendix B

Weather Parameters for Sag-Temperature Calculations

The weather parameters used for the calculation of the current ratings in section 6.4.1.2 are presented in the table B.1. These are based on Cigré and IEEE recommendations [100, 102, 123].

Table B.1: Weather parameters used for current-temperature calculations.

Parameter	Value	Unit
Wind speed	0.6	m/s
Ambient temperature	20	°C
Elevation of conductor above sea level, H_e	0	m
Absorptivity of conductor surface, α	0.5	-
Emissivity of conductor surface, ε	0.5	-
Hour angle, Ω, [-180;180], 0 = noon	-37	°
Latitude	55	°
Azimuth of the line, Z_l	45	°
Day of the year	161	-
Atmosphere – clear (0) or industrial (1)	0	-

The many data for sun radiation (hour angle, latitude, azimuth of line, day of the year and atmosphere type) result in a value of 980 W/m.

Appendix C

Transient Simulations on Overhead Line Systems

This appendix is based on excerpts from the two papers [126] and [132], which were written during the PhD project.

Depending on what is to be simulated different steps can be included in the simulation model. The different steps are a Monte Carlo simulation, an electrogeometric model and the transmission line model.

The transmission line model represent the simulated transmission line when subjected to a transient event and is the basis for simulating transmission lines under transient occurrences.

Above the transmission line model, an electrogeometrical model can be implemented. The electrogeometrical model simulates where a lightning stroke will strike an overhead line, e.g. shield/ground wires, phase conductors, towers or nearby ground. An electrogeometrical model can be used to determine how well protected an overhead line is by its shield/ground wires.

For multiple simulation of transients on an overhead line system, a Monte Carlo control scheme can be used to control different input parameters and log predetermined output parameters.

With all three layers it is possible to make lightning studies of overhead lines based on statistical data for lightning and overhead line parameters whereby a good representation of the failure rate of an overhead line can be reached.

Monte Carlo Simulation

Use of Monte Carlo simulations to determine the lightning performance of transmission lines was introduced by Anderson [133] and has since been widely accepted [134, 135, 136].

A Monte Carlo simulation that describes the lightning performance of overhead transmission lines is a multiple run simulation wherein different parameters, e.g. lightning current amplitude and front time, are generated based on observed probability density functions (pdf) at every run of the simulation model. Thus after several runs (usually in the thousands) different situations of lightning strokes to a transmission line are simulated. The flashover probability of the line F/N (flashovers per run) and the ground flash density Ng expected around the line can then be used to estimate the yearly failure rate per 100 km n_f.

$$n_f = N_g \cdot 100 \cdot F/N \tag{C.1}$$

However an important factor in the Monte Carlo simulation is the lightning attachment point on a transmission line which as mentioned is described by use of an electrogeometrical model.

Electrogeometric Model

An electrogeometric model (EGM) describes the attractive radius of shield wires, conductors and ground – thus estimating the most likely attachment point of a lightning stroke.

Several variations of electrogeometric models have been developed [134, 137]. Some are simple to implement whereas others take into account strike angle dependent entry points and three dimensional models considering the differences in shielding from shield wires and towers' protection zones.

The method preferred here is one of the simpler kind suggested by Eriksson [138, 139]. Eriksson's electrogeometric model considers the attractive radius Ra' of horizontal conductors as a function of conductor height above ground H and lightning current amplitude I, in contrast to many other EGMs which only considers stroke amplitude.

$$Ra' = 0.67 \cdot H^{0.6} \cdot I^{0.74} \tag{C.2}$$

Eriksson's model also differs from others because (C.2) is applied to both shield wires and conductors whereas other EGMs have different equations for shield wires and conductors. Furthermore, Eriksson's model assumes that all lightning strokes not attracted to the transmission line (conductor or shield wire) have struck ground. Other EGMs include modelling of the earth's attractive radius.

Though Eriksson's EGM is referred to as a simple model, it has still shown good correlation with observation of lightning failures on transmission lines [134, 139].

It should be noted that for calculation carried out in the PhD project, the lightning stroke is modelled as having only a vertical direction. Thus the intrusion angle is zero and the result of the EGM is simple intervals along the horizontal axis describing either a hit to shield wires, conductors or earth.

Transmission Line Model for Transient Simulations

A transmission line model for transient simulations consists of several parts. The different parts and how they are represented for a transient study are presented in the following subsections. For the work carried out in connection with the PhD project the transients simulation program PSCAD/EMTDC 4.2.1 [140] has been used to carry out the simulations.

Line Representation

Several different models can be used to represent overhead lines for transient simulations and in PSCAD three different models are available. The most accurate model is however the time domain multiconductor frequency dependent lossy transmission line representation available in PSCAD and it is this model that have used in the work for the PhD project.

For studies of the overvoltages that arise on a line due to lightning strokes to an overhead line, only a section of the transmission line needs to be represented in the model. Therefore a line is represented by eight 300 m line sections, such that there is at least three sections to each side of the section or tower (connection of two sections) that is struck by lightning.

As only a section of the line is modelled it is necessary model the line ends as reflectionless, since reflections from the open ends will lead to higher overvoltages than can be expected. Another solution is to increase the length of the line ends to such an extent that the length of the line ends delays the reflections to after the time of interest in the model.

The phase voltage of the system should also be represented in model since the system voltage will give an offset of the lightning overvoltage in the system and thus in some case give higher voltages across clearances and insulators than else expected. The phase voltages are modelled with a three phase 400 kV voltage source at 50 Hz. The phase angle of the system is randomly generated at every run as a uniformly distributed variable [141, 142].

Lightning

Several different models for the lightning wave exists in the literature. The most known model is perhaps the double exponential function, which have been used for some of the analytical work carried out.

The double exponential wave describes the lightning impulse current $i(t)$ by a front time t_f , tail time t_h, amplitude I_0 and amplitude correction factor η [141].

$$i(t) = \frac{I_0}{\eta}\left(e^{-\frac{t}{t_f}} - e^{-\frac{t}{t_h}}\right) \tag{C.3}$$

I_0 and t_f are generated as log-normal distributed parameters at every run of the Monte Carlo simulation with a mean value $\mu = 34kA$ and $\mu = 5.63$ and standard deviation $\sigma = 0.74kA$ and $\sigma = 0.576$, respectively as per Cigré lightning data. The tail time can be kept constant or also varied statistically as the previous parameters. Whether or not the tail time needs to be varied depend on the purpose of the study. For overvoltage studies the tail time of the lightning is not important. However for studies of components ability to handle the energy in the lightning flash, the tail time must be included with it's statistical distribution for a good representation of in-service conditions [137, 141].

For a more accurate representation of the lightning wave, the double exponentional function can be replaced by the Cigré lightning wave model. This model will not be presented here. The model can however be found in [141].

Tower Representation

To calculate the overvoltage on overhead lines also the towers of the line have to be represented in the model. Several different tower models can be found in the literature and no single model is at the moment preferred.

In the present work, it has be chosen to construct tower models based on [143]. Here the tower is represented by a multiconductor model where the surge impedances are determined based on the tower structure geometry. The tower arms are represented separately in the model and thus calculating the voltage across insulators can easily be done. For an example of the application of the tower model, refer to [126].

Besides the tower structure itself also the footing impedance of the tower must be represented in transient models. The footing impedance of the tower is a nonlinear resistance R_T, which is dependent upon the low frequency tower footing resistance R_0, the actual lightning current through the resistance I and the limiting current to initiate soil ionisation

I_g [141, 142].

$$R_T = \frac{R_0}{\sqrt{1 + \frac{I}{I_g}}} \tag{C.4}$$

I_g is determined from the soil resistivity ρ, the soil ionisation gradient E_i and R_0 by equation (C.5).

$$I_g = \frac{E_i \rho}{2\pi \cdot {R_0}^2} \tag{C.5}$$

R_0 is generated at every run as part of the Monte Carlo simulation based on a measured or assumed distribution.

Clearance and insulator flashover

Insulators and clearance flashover is included by means of a Leader Progression Model (LPM) which divides the clearance flashover into three stages [141, 142, 144]. The three stages are corona inception time t_i, streamer propagation time t_s and leader propagation time t_l, so that the total time to flashover t_c can be expressed as in equation (C.6).

$$t_c = t_i + t_s + t_l \tag{C.6}$$

The corona inception time t_i is neglected in the equation above since it is reached relatively fast. The streamer propagation time, t_s, is evaluated based on (C.7) from the maximum voltage gradient E across clearance before flashover and the average gradient at critical flash-over gradient E_{50}.

$$\frac{1}{} = 1.25 \frac{E}{E_{50}} - 0.95 \qquad [\mu s^{-1}] \tag{C.7}$$

The leader propagation time t_l is found calculated by equation (C.8) and is dependent upon the voltage across the clearance $u(t)$, the leader length L, the clearance length g and the clearance type and voltage polarity dependent constants K and E_0 (see table C.1).

$$\frac{dL}{dt} = K \cdot u(t) \cdot \left(\frac{u(t)}{g - L} - E_0 \right) \tag{C.8}$$

Flashover will only take place if the leader crosses the clearance across the insulator ($L \geq g$) [141, 142].

Table C.1: Constant to be applied in equation (C.8).

Configuration	Polarity	K $m^2/(V^2s)$	E_0 kV/m
Clearance, post and longrod insulators	+	$0.8 \cdot 10^{-6}$	600
	-	$1.0 \cdot 10^{-6}$	670
Cap and pin insulators	+	$1.2 \cdot 10^{-6}$	520
	-	$1.3 \cdot 10^{-6}$	600

The LPM model is used to represent clearances and insulators as a mini-mum at the tower near the strike point of the lightning stroke.

For all towers the insulator is equivalated by a capacitance between the phase and tower of 100 pF/unit (a unit, is one cap-and-pin insulator disc) to represent the coupling between towers and phases [142]. This representation is further used in parallel with the LPM at the tower where the lightning stroke is simulated.

A more simple approach than the LPM to represents insulators and air gaps is to consider the critical flashover voltage (CFO) for negative impulses CFO^- dependent upon clearance length g as given in IEC 60071-2 [145].

$$CFO^- = 700 \cdot g \tag{C.9}$$

Statically the CFO can be described by a Weibull distribution with a mean value equal to the CFO^- and a deviation equal to 5 % CFO^- (9 % for insulators).

Surge Arrester Representation

Line surge arresters are modelled according to the IEEE Arrester Model [146]. The arrester is in the IEEE model represented by two nonlinear volt-current characteristics, A_0 and A_1, two L,R-filters and a capacitance C in parallel with A_0. The arrester model is depicted in figure C.1.

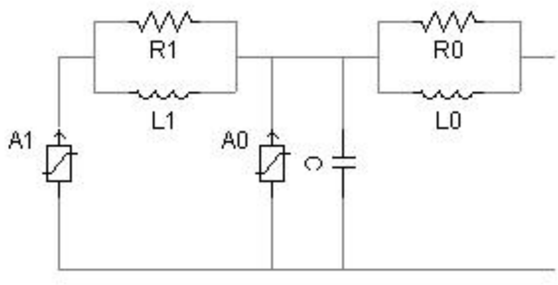

Figure C.1: IEEE surge arrester model [146].

The parameters of the model are determined based on information given in the arrester data sheet. These data are arrester height d_{sa} in metres and number of parallel metal oxide columns n_{sa}. Thus the following equations should be applied to determine L_0, L_1, R_0, R_1 and C.

$$L_0 = 0.2 \cdot d_{sa}/n_{sa} \qquad [\mu H] \tag{C.10}$$

$$L_1 = 15 \cdot d_{sa}/n_{sa} \qquad [\mu H] \tag{C.11}$$

$$R_0 = 100 \cdot d_{sa}/n_{sa} \qquad [\Omega] \tag{C.12}$$

$$R_1 = 65 \cdot d_{sa}/n_{sa} \qquad [\Omega] \tag{C.13}$$

$$C = 100 \cdot n_{sa}/d_{sa} \qquad [pF] \tag{C.14}$$

Some parameter adjustment can be necessary to get a good correspondence between the model and data from the arrester data sheet.

Statistical distribution

Several of the parameters generated in the Monte Carlo simulation have different statistical distributions. For the lightning impulse amplitude and front time the log-normal distribution is assumed whereas the tower footing impedance is assumed normal distributed. Other parameters can be described as uniformly distributed which is the case with lightning horizontal position and the phase angle of the system voltage.

The uniformly distributed parameters are generated by a random number generator. For variables that need a statistical distribution the following method can adopted.

For each variable two random values are generated; a candidate value e.g. for the lightning amplitude and a random number between zero and the maximum pdf value. The candidate value is accepted if the accompanying number is smaller than the probability value of the variable. A similar method is used in [134].

Appendix D

Lightning Studies

This appendix is based on experts from [132], a paper published during the PhD project.

Based on guidelines in appendix C, simulations of lightning transients on a 400 kV overhead line are carried out in the transients simulation program PSCAD 4.2.

The 400 kV line is modelled with 300 m spans and 20 line sections are represented in the model. The tower model is based on Energinet.dk's "Design Tower" – a delta tower with two shield wires.

For the full model with shield wires represented, a lightning impulse of approximately 100 kA 1.2/50 μs can be applied to the shield wires of the system without flashover of the insulators on the tower subjected to the impulse. This is a reasonable representation of the expected behaviour. Lightning hitting other phases are not considered here.

Figure D.1 shows the maximum absolute surge voltage (line to ground) in the upper phase of the tower when the upper phase (or shield wire) is subjected to 100 kA lightning impulse. This is done in relation to the tower struck. The struck tower is marked 0.

The original system with two shield wires and no arrester is denoted "2 Shield Wires – n = 0". The letter n is here used to give the ration between arresters and the number of towers.

$$n = \frac{\text{Number of arrester}}{\text{Number of towers}} \tag{D.1}$$

The system is then simulated without shield wires and equipped with arrester. Only lightning hits to the top phase are considered. The arrester is modelled as mounted between the top of the tower and upper phase. The system is simulated without any protection (n = 0), with an arrester in every third tower ($n = 1/3$), an arrester in every second tower ($n = 1/2$) and with an arrester in every tower ($n = 1$) connected to the upper phase.

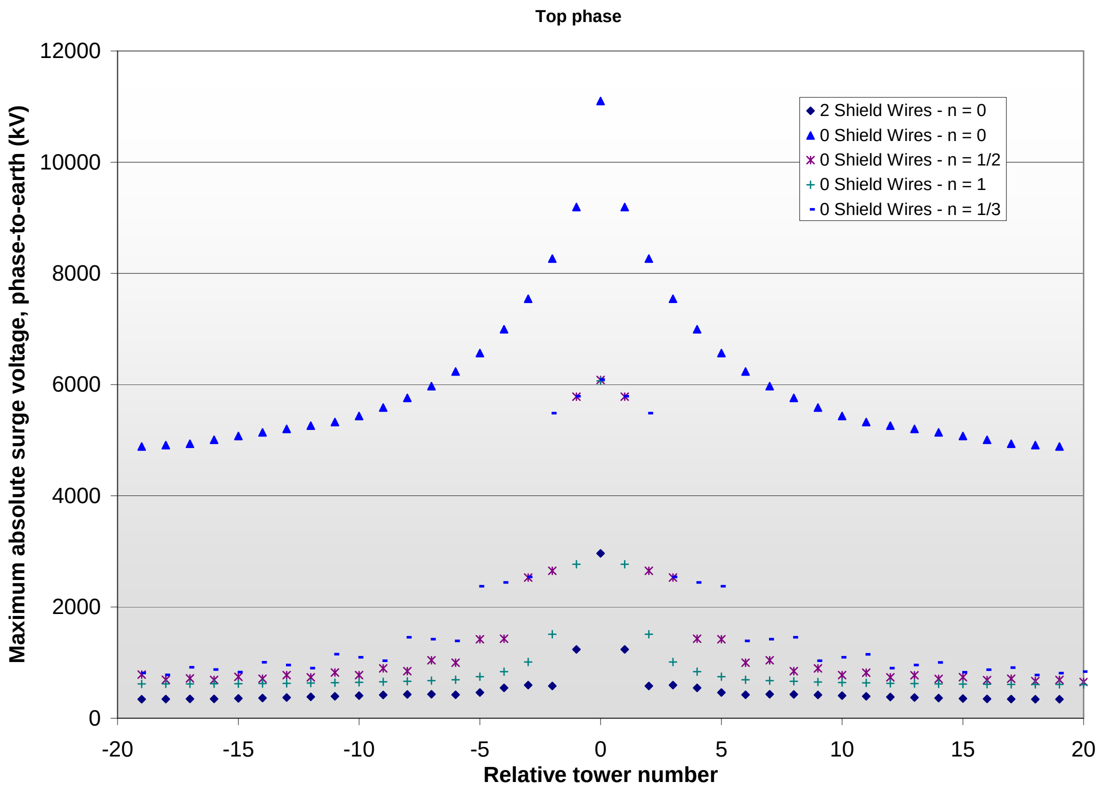

Figure D.1: Maximum absolute surge voltage (line to ground) under 100 kA lightning impulse with different arrester configurations - Upper phase voltage.

When the line is unprotected the phase voltage is raised considerably along all towers. This also applies for the lower hanging phases. The result is that several phases of the system flash over.

Arresters are then inserted in the system – for every third ($n = 1/3$), second ($n = 1/2$) and finally every tower ($n = 1$). The results are given with the protected and unprotected line in figure D.1. From this it can be seen that equipping the line with arresters lowers the phase voltage – as expected.

It can also been seen from Figure 3 that as the number of arresters are increased along the line, the phase voltage decreased faster as lightning surge travels along the conductor. However the maximum absolute surge voltage of the system cannot be lowered more than to 6 MV independent upon the number of arrester mounted on the line. This however does not mean that the insulators at the struck tower flash over since the voltage given in figure D.1 in the line to ground voltage of the phases and not across the insulator.

Even though the struck tower does not flash over if equipped with an arrester, the rest of towers can still have flashovers along the insulators. If the neighbouring towers are not protected with surge arrester the voltage across the insulator can developed to such an extent that flashover will take place. In table D.1 it is given if flashover takes place along any insulator in the system in the different cases.

Table D.1: Summery of simulation results [132].

n	No. of shield wires	Flashover
0	2	No
0	0	Yes
1/3	0	Yes
1/2	0	Yes
1	0	No

From the table D.1 it can be observed that only the system with arresters at every tower connected to the upper phases prevents flashover along the line. It can further be seen from Figure 3 that the n = 1 case has a close resemblance to the shield wire protected line about four towers away from the strike point. Thus a good protection of the line can be achieved when only considering lightning strikes to the upper phase.

Discussion

Using line surge arresters for lightning protection instead of shield wires must be considered carefully. As have been shown in the results section the maximum phase voltage in an arrester protected system can be reduced to the level close to that of a shield wire protected transmission systems. This consideration is though based upon that only the upper phase will get hit by lightning. In reality, as observations and the geometric line model will confirm [141], the outer phases of the delta configuration are also exposed to lightning hits.

Thus to fully consider the implications of implementing line surge arresters as the only mean of lightning protection a flashover rate study should be carried out. Thus hits to the lower phases would also be included in the study. Other measures of improving the reliability of an arrester protected system could also be considered. One of these measures could be increasing the clearances in the tower top geometry and thus increasing the insulation of the lines. Again this will result in a relatively larger tower top geometry which must be weighed against the reduction in number of conductors.

Removing shield wires from a 400 kV overhead lines system will result in a lessened visual impact of the lines. The line number in case of a single system 400 kV line is reduced from 5 to 3. This reduces the perceive space created between the phases. However the insertion of LSAs in tower tops will result in a denser impression of the towers. Making the tower top more ”heavy” to look upon. The weight of the different measures must be considered against one another to find which solution is the least disturbing to the eye. Thus no clear indication on which solution is the better can be given here, however it is the authors’ opinion that reduction of the conductor number by removing the shield wires would be more aesthetically correct.

To fully evaluate the performance of line surge arrester protected system it is necessary to carry out a flashover rate study. Also multiple strokes to the line and the resulting thermal stress of the arresters due to the energy build up in the arrester should be further examined.

Conclusion

Lightning protection of 400 kV transmission lines without shield wires requires equipment of each tower with line surge arrester of the upper phases in order not to reduce the lightning protection performance of the system under direct stroke to the protected phase.

Lines equipped solely with arrester at every other ($n = 1/2$) or every third ($n = 1/3$) tower will experience flashover independent upon whether or not lightning hits at an arrester equipped tower or not. However the number of flashovers will not be the same along the line since the different arrester configuration will give different phase voltages along the line.

The use of line surge arrester does though present a way of reducing the visual disturbance caused by overhead transmissions lines. This is through reduction of the total number of conductors needed between towers.

Equipping a 400 kV transmission line with line surge arrester still needs to be further investigated through flashover studies and evaluation of the need maintenance of arresters.

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ISBN: